HYDROLOGIC RESPONSE DURING SNOWMELT IN THREE STEEP HEADWATER CATCHMENTS: RINGROSE SLOPE, SLOCAN VALLEY, BRITISH COLUMBIA

by

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ABSTRACT

Using a combination of hydrometric measurements, geochemical and isotopic tracers, and analysis of historical data, three steep headwater catchments of the Slocan Valley, British Columbia, Canada, were described and contrasted in terms of runoff processes and pathways during the 2002 freshet. Streamflow responsiveness was shown to be related to the degree to which connectivity between source areas of meltwater and stream channels was maintained as the snowline progressed upslope. The Thickett Creek catchment displayed the most sluggish streamflow response and was dominated by relatively deep subsurface flow throughout the freshet. The Gurn Brook catchment demonstrated the flashiest streamflow response and experienced significant channel flow relative to the other catchments, with subsurface flow maintaining connectivity between source areas and the channel network. The Gurn Spring catchment demonstrated streamflow response intermediate between the other catchments; however, high unit runoff and unit peak flow relative to the other catchments suggested significant inter-catchment transfers of bedrock groundwater into the Gurn Spring catchment. While a soil-water reservoir within Gurn Spring contributed to streamflow during peak flow, contributions from bedrock groundwater dominated during baseflow and hydrograph recession.

Attempts to perform an isotopic hydrograph separation were confounded by the complex variation in new-water isotopic concentrations in both time and space. Qualitative interpretation of isotopic results indicated the dominance of old water contributions during baseflow, with increasing new water contributions during hydrograph rise. Similar isotopic concentrations between meltwater and streamwater at the time of peak flow prevented resolution of the relative contributions from old and new-water at that time.

Relative to other studies, the study catchments displayed surprisingly little diurnal streamflow response during snowmelt. Possible explanations for this are presented and discussed, as are the potential impacts of forest harvesting and road construction on hydrologic response in the three catchments. Finally, the implications of the research findings for catchment-scale modelling were examined.

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CHAPTER 1
INTRODUCTION

1.1 BACKGROUND

The processes and pathways by which water moves through a catchment to its outlet exert a control on the timing, magnitude and chemistry of streamflow. These processes can be influenced by land use activity, such as the construction of logging roads (e.g. Megahan, 1972; Luce and Wemple, 2001; Wemple, 2003). An understanding of runoff processes is therefore essential for predicting the effects of land use, such as forest harvesting, on water quantity and quality.

Many residents of southern interior British Columbia derive their water supply from small, weakly incised streams draining steep valley walls, locally referred to as "face unit" streams (Forest Practices Code, 1999). To address the potential effects of forest harvesting on these small streams, a paired-catchment experiment involving three streams was initiated in the late 1980s on the Ringrose Slope in the Slocan Valley in the southern interior of British Columbia. One of the catchments was to be subjected to logging and road construction, with the other two being maintained as untreated experimental controls. Two studies were initiated in 2001 to complement the paired-catchment experiment, one to study runoff processes, the other to apply a spatially distributed, physically based hydrologic model. The research presented in this thesis examined pre-harvest snowmelt runoff processes in the three catchments to provide a basis for interpreting the results of the paired-catchment study. It will also provide data for internal validation of the hydrologic simulations. The next section presents a review of the current understanding of snowmelt runoff processes in forested catchments in order to provide the scientific context for the research objectives.

1.2 REVIEW OF RUNOFF GENERATION IN TEMPERATE FORESTED CATCHMENTS

1.2.1 Runoff processes and pathways

Runoff processes encompass both the sources of water, usually distinguishing between old (pre-event) and new (event) water, as well as the pathways by which water travels to the stream channel. The four major runoff pathways are: (1) Overland Flow (Q_o); (2) Subsurface Storm Flow (SSF) or Throughflow (Q_t); (3) Groundwater Flow (Q_g); and (4) Direct Precipitation onto the Channel (Q_p) (Figure 1.1; Ward and Robinson, 2000). Overland flow can be generated by two processes: Hortonian Overland Flow (HOF) and Saturation Overland Flow (SOF). The former occurs when the rate of water input exceeds the infiltration capacity of the soil and excess rainfall or snowmelt discharges over the land surface (Horton, 1933). Consequently, the temporal source of HOF is new rainwater and the runoff pathway is overland. Saturation Overland Flow occurs when the water table rises to the ground surface, creating saturated conditions (Dunne and Black, 1970a, b). It comprises Direct Precipitation onto Saturated Areas (DPSA) and Return Flow (RF). The former involves the deflection of inputs of rain or meltwater onto saturated areas overland towards the stream channel, whereas RF involves the exfiltration of subsurface water that is then free to travel overland to the stream channel. Saturation overland flow can therefore be a mixture of old subsurface water and new water from either rainfall or snowmelt. Subsurface Storm Flow occurs when infiltrated water flows laterally through the upper soil horizons either as unsaturated flow or as a perched water table above the main saturated zone (Freeze, 1974). Groundwater flow is that portion of the subsurface flow that moves laterally through the permanently saturated zone to the stream channel (Ward and Robinson, 2000).

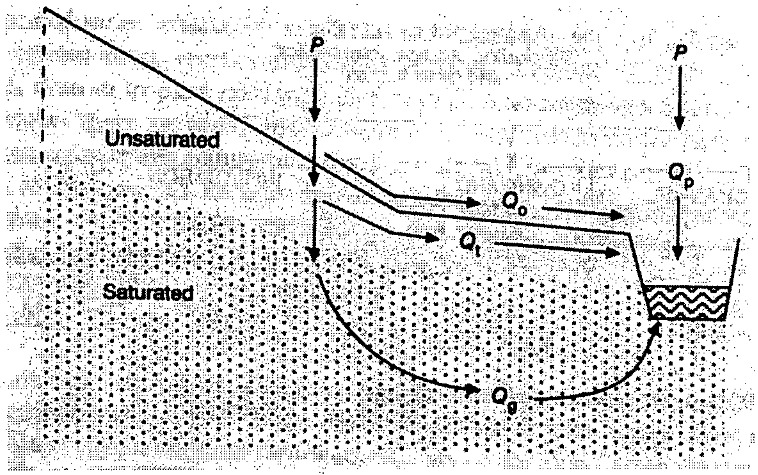

Figure 1.1. Runoff pathways (from Ward and Robinson, 2000).

Studies in forested environments have generally discounted HOF as a significant runoff process due to the high infiltration capacity of forest soils (Sidle et al., 2000). In snowmelt dominated systems, HOF may be significant where impermeable frost develops at the ground surface or where an impermeable ice layer forms at the base of the snowpack (Dunne and Black, 1971; Jordan, 1978; Price and Hendrie, 1983; Nyberg et al., 2001). In near-channel environments where the water table and capillary fringe are close to the ground surface, as in wetlands and riparian corridors, SOF is the dominant runoff process (Freeze, 1972; Freeze, 1974; Sidle et al., 2000). Subsurface stormflow has been suggested as a dominant runoff process on forested slopes in areas characterized by shallow soil horizons of high permeability at the surface, convex slopes feeding deeply incised channels, and high saturated hydraulic conductivities (Freeze, 1974). Rapid downslope flow through forest occurs via preferred pathways, such as macropores formed by decayed root channels (Mosley, 1979; Turton, 1992; Hutchinson and Moore, 2000; Noguchi et al., 2001). Preferential flow through fractured bedrock has also been cited as a possible means by which water may move downslope and enter the channel network (Laudon and Slaymaker, 1997). The ability of SOF and SSF to contribute to rapid streamflow response is linked to the variable source area concept, which essentially treats saturated areas as extensions of the channel network. As saturated areas grow and shrink in response to water inputs, so do the volumes of SSF, tapped and discharged as return flow, and DPSA entering this extended channel network (Dunne and Black, 1970a, b; Dunne and Black, 1971; Freeze, 1972, Freeze, 1974).

Sidle et al. (2000), working in a 2.48 ha catchment at Hitachi Ohta Experimental Watershed, Japan, developed a conceptual hydrogeomorphic model to describe the spatially distributed nature of stormflow response over a period of rainfall and increasing soil moisture. Sidle et al. identified three hydrogeomorphic units, which are essentially source areas that display distinctive hydrologic behaviour: (1) narrow riparian corridors; (2) linear hillslopes; and (3) geomorphic hollows or zero-order basins. During dry conditions the majority of stormflow was generated from channel interception and SOF in narrow riparian units. As wetness increased, the lower extent of the linear hillslope units linked with riparian corridors to produce subsurface flow from the soil matrix and augment streamflow. Further wetting resulted in subsurface flow propagating over larger hillslope areas, the commencement of preferential flow, and "tapping" of geomorphic hollows, thereby linking all three hydrogeomorphic units and further augmenting streamflow. As the study basin was relatively small and water inputs (rainfall) were assumed uniform over the basin area (Sidle et al., 2000), no attempt was made to describe the interaction between spatially distributed water inputs and the spatial distribution of the resulting runoff processes.

The hydrogeomorphic concept is a conceptual framework for examining temporal and spatial variation in the characteristics of catchment flowpaths and hydrologic response. This is achieved by focussing on the connectivity between hydrogeomorphic units (i.e., source areas possessing relatively homogeneous hydrologic and geomorphic characteristics) in order to generate a conceptual model of catchment response (Sidle et al, 2000). Other studies have adopted the hydrogeomorphic concept in principle, if not in name. Ladouche et al. (2001) examined the runoff response from three spatially distinct hydrologic zones within the Strengbach catchment, France. Hangen et al. (2001) documented the temporal process of stormflow generation from near-stream and hillslope areas as follows: (1) rapid delivery of water by infiltration and soil water displacement at near-stream areas supplemented by SOF; (2) rapid depletion of the near-stream soil and groundwater reservoir; and (3) delayed subsurface water contribution from hillslope areas. Spence and Woo (2003) analysed runoff processes in a subarctic Canadian Shield catchment in terms of the interactions between bedrock upland and soil-filled valley units.

1.2.2 Methods for studying runoff processes

Methods employed in the study of runoff processes vary in their uses and limitations A number of isotopic tracer studies have revealed that pre-event water dominated streamflow in rainfall and snowmelt driven systems and produced rapid streamflow response (Sklash and

Forvolden, 1979; Pearce et al., 1986; Sklash et al., 1986; Dewalle et al., 1988, Moore, 1989; Buttle and Sami, 1992; Sueker et al., 2000; Ladouche et al., 2001). Geochemical tracers have been used to separate streamflow into components based on the chemistry of specific contributing waters, or end-members (Christophersen et al., 1990; Hooper et al., 1990; Sueker et al., 2000; Burns, 2001; Katsuyama et al., 2001). End-members have been defined in terms of chemical differences between riparian vs. hillslope waters (Hooper et al., 1990; Hooper et al., 1998), surface vs. subsurface flowpaths (Wels et al., 1991; Sueker et al., 2000), and between subsurface flowpaths at different depths (Christophersen et al., 1990; McGlynn et al., 1999).

Hydrometric methods involve measurement of hillslope flow (e.g., by using interception trenches and overland flow collectors) and subsurface water potential (using tensiometers, wells and piezometers), and have been used to identify the mechanisms responsible for the typically large proportions of pre-event water contributing to stormflow, as inferred from isotopic studies. These include groundwater ridging, saturation overland flow, translatory flow, kinematic waves, and release of water from surface storage (Buttle, 1994). Integrated tracer studies, which combine hydrometric measurements with tracer analysis, have underscored the risks of inferring streamflow generating mechanisms from tracer studies without supporting evidence from hydrometric measurements and observation (Buttle and Sami, 1992).

Ladouche (2001) recommended that hydrologic studies employ "complementary approaches" in time and space. Tracer studies should employ both isotopic and geochemical tracers if they are to identify both runoff pathways and temporal sources of runoff (Ladouche, 2001).

A range of chemical species has been used to provide information on flow paths. Dissolved organic carbon (DOC) has been employed to identify runoff contributions from organic-rich surface and shallow subsurface waters (Ladouche et al., 2001; Shanley et al., 2002) and from different soil depths within the riparian zone (McGlynn et al., 1999). Silica and the major cations Ca, Mg, Na and K have been used extensively to identify runoff contributions from deeper subsurface pathways characterized by long contact times in the presence of mineral soils and/or bedrock (Christophersen et al., 1990; Hooper et al., 1990; Wels et al., 1991; Anderson et al., 1997; Buttle and Peters, 1997; Sueker et al., 2000; Ladouche et al., 2001). Subsurface flow contributions have also been inferred using temperature (Kobayashi, 1985; Kobayashi et al., 1999) and electrical conductivity (Kobayashi, 1986; Kobayashi et al., 1999; Laudon and Slaymaker, 1997) by employing a mass-balance equation and variations on Hall's mixing models (Hall, 1971). Fluorescence properties of dissolved organic carbon have been employed to identify runoff contributions from the transient saturated zone (Katsuyama and Ohte, 2002).

1.2.3 Distinctive characteristics of snowmelt runoff processes

Most studies of runoff processes in steep forested catchments have focused on rainfall events (e.g., DeVries and Chow, 1978; Anderson et al., 1997; Montgomery et al., 1997; Hoeg et al., 2000; Katsuyama and Ohte, 2002). Snowmelt runoff processes differ from rainfall-runoff processes due to the distinctive spatial variation in the depth and attributes of the snowpack, in meltwater generation (e.g., in relation to aspect, elevation and vegetation cover), as well as the effect of internal snowpack processes influencing percolation rates. Snowmelt runoff processes can be viewed as a function of: (1) the spatial distribution of snow-water equivalent (SWE) and the rate of melt (controlled by meteorological variables); (2) internal snowpack processes such as metamorphism, phase changes and percolation; and (3) the physical processes and characteristics that govern the movement of meltwater through the basin (Ward and Robinson, 2000). The distribution of the snowpack and the rate of melt will influence the timing, location, and magnitude of meltwater inputs. For example, alpine catchments may experience a positive net balance of snow storage at higher elevations during years of high snow accumulation, resulting near-normal catchment runoff despite above average snow-water-equivalents (Teti, 1979). Dunne and Black (1971) observed that the lag-time between the onset of melt and runoff initiation was primarily controlled by the depth of the snowpack. There was an approximately linear relation between the depth of the snowpack and the lag between the onset of snowmelt and runoff initiation.

Early in the melt period internal snowpack processes may dominate (Colbeck, 1979), and are influenced by the physical properties of the snowpack (Marsh and Woo, 1984, 1985). For example, dye tests by Jordan (1978) in a small alpine basin in McGillivray Pass, British Columbia, revealed that the flow of meltwater within the snowpack was affected by irregularities in the snowpack such as ice layers and snow layers of different textures and hydraulic conductivities. The rate at which meltwater can be transmitted through the snowpack greatly affects the timing of the streamflow response (Ward and Robinson, 2000). As mentioned earlier, the presence of impermeable ground frost can limit infiltration at the snow-soil interface (Price and Hendrie, 1983; Thunholm et al., 1989; Stähli et al., 1996); however, many studies in forested environments have found either no impermeable frost layer (Moore, 1989); or its effects on runoff response to be negligible (Roberge and Plamondon, 1987; Shanley and Chalmers, 1999). Later in the melt period, streamflow response is governed by the movement of meltwater through the drainage basin by means of the runoff pathways outlined above.

Runoff processes in steep, snowmelt dominated catchments are further complicated by elevational changes in hydrogeomorphic setting and the upslope movement of the snowline resulting in spatially variable meltwater inputs. Of the studies focused on catchment runoff processes and pathways during snowmelt in temperate forested regions, only the study by Sueker et al. (2000) was conducted in a mountainous environment and none was conducted in steep headwater catchments (Table 1.1). Studies conducted in British Columbia have examined runoff processes and pathways in alpine catchments (Zeman and Slaymaker, 1975; Laudon and Slaymaker, 1997), and the processes of meltwater generation and the routing of water through the snowpack (Braun 1980, Jordan, 1983). However, little attention has been given to the study of runoff processes and pathways in steep, temperate, forested headwater catchments of the Pacific Northwest during snowmelt. In particular, there appear to have been few significant contributions to the study of catchment runoff processes during snowmelt from temperate forested areas of either coastal or interior British Columbia.

Table 1.1. Catchment-scale studies of runoff processes during snowmelt in temperate forested environments.

Study	Catchment Relief (m)	Catchment Area (ha)	Steepness Index ($S^* = (Relief)/A^{0.5}$)	Location
Buttle and Sami (1992)	14	3.12	8	Perch Lake watershed, Ontario
Kendall et al. (1999); McGlynn et al. (1999)	155	40.5	24	Sleepers R. watershed W-9, Vermont
Shanley and Chalmers (1999)	581	11100	5.5	Sleepers R. watershed W-5, Vermont
Kobayashi (1985, 1986)	320	128	22	Uryu R., Hokkaido Island, Japan
Maulé and Stein (1990)	87	68	11	Lac Laflamme basin, Québec
Hazlett et al. (2001)*		4.62, 4.06		Turkey Lakes watershed, basins 31 and 47, Ontario
Moore (1989)	30	5.3	13	Hermine basin, Laurentians, Québec
Sueker et al, (2000)	1193 – 1820	780 – 10440	15 – 53	6 Catchments within Rocky Mtn. Nat. Park, Colorado
Zeman and Slaymaker (1975)	1220	2160	26	Miller Creek basin, Pacific Range, British Columbia Coast Mountains

* Information regarding catchment relief was not available. Consequently no steepness index was calculated these basins.

1.3 OBJECTIVES, QUESTIONS AND RESEARCH HYPOTHESES

The objective of this study is to compare the spatial and temporal distribution of runoff processes in response to spatially and temporally variable snowmelt inputs among three face unit catchments in the southern Interior of British Columbia. The hydrogeomorphic concept will be adopted as a framework within which the following specific question can be addressed:

1. What are the dominant runoff pathways and how do they interact and evolve over the snowmelt period in response to spatial and temporal variation in water inputs?

It was anticipated that a comparison of the three catchments would reveal differences in snowmelt runoff processes due to differences in their associated hydrogeomorphic characteristics. The following hypotheses have been proposed as alternatives to the null hypothesis that no difference in catchment runoff processes will be observed (these hypotheses draw upon catchment descriptions presented in Chapter 2: Methods, Section 2.2: Field Site):

1. Differences in catchment streamflow response are related to the degree to which connectivity between stream channels (i.e. areas capable of rapidly transmitting water from source downslope) and meltwater source areas is maintained as the snowline progresses upslope.
2. Thickett Creek, having a short, poorly incised permanent channel will experience an early disconnect between source areas and stream channels as the snowline progresses upslope. Runoff pathways will be dominated by subsurface flow through deeper soil layers and subject to long contact times. Streamflow response in Thickett Creek will be sluggish relative to the other streams
3. Gurn Brook, having a deeply incised stream channel extending into the upper catchment, will experience the greatest degree of connectivity between meltwater source areas and the stream channel as the snowline progresses upslope. Surface flow (e.g. channel flow or saturation overland flow) and shallow subsurface flow characterized by short contact times will constitute important runoff pathways in the Gurn Brook catchment. Streamflow response in Gurn Brook will be flashy relative to the other streams.
4. Gurn Spring, having a moderately incised channel of moderate length and small catchment area, will exhibit an intermediate degree of connectivity between source areas and the stream channel relative to the Gurn Brook and Thickett Creek catchments.

Runoff pathways will be comprised of a mixture of deep subsurface flow and surface/shallow subsurface flow. Streamflow response will be neither so flashy as Gurn Brook nor so sluggish as Thickett Creek.

1.4 STRUCTURE OF THE THESIS

The remainder of this thesis is composed of four chapters. Chapter 2 provides an introduction to the study area and an overview methodology and data analysis. Chapter 3 presents results of the data analysis and Chapter 4 provides interpretation and discussion of results in the context of the research objectives. Chapter 5 contains a summary of key findings and makes recommendations for future research.

CHAPTER 2
METHODS

2.1 STUDY AREA

2.1.1 Location

The study area was located at Ringrose Slope, a steep southwest-facing side wall of the Slocan River watershed, in the West Kootenay region of British Columbia (Figure 2.2, inset). The Slocan River watershed covers an area of approximately 340,000 ha, and is located in the Selkirk Mountains, in what is referred to as the "wet interior" forest zone. Steep terrain dominates the Slocan Valley landscape. Narrow flat valley bottoms, changing abruptly to steep, broken side walls, characterize the main valley and its tributaries, with slopes often exceeding 30 degrees or 60% (Silva Forest Foundation, 1996). Ringrose Slope marks the western toe of the Kokanee Range of the Selkirk Mountains further to the east. Directly across the main valley from Ringrose Slope lies the Valhalla Range of the Selkirks. The terrain of Ringrose Slope is that of a steep (slope gradients dominantly in excess of 20°) valley side-wall accentuated by rock outcrops and small cliff bands, and dissected by small headwater streams.

2.1.2 Climate

The climate of the Slocan Valley can be generally described as continental, with cold winters and hot summers. During winter and early spring, cold air travels down slopes and stream gullies effectively extending colder conditions of the upper elevations into lower elevations and along stream channels (Silva Forest Foundation, 1996). Monthly mean daily temperatures, based on 1961-1990 climate normals measured at the Atmospheric Environmental Service (AES) climate station in New Denver (570 m elevation), range from –3.3 °C in January to 18.7 °C in August. Total annual precipitation at New Denver is 866 mm, of which the majority (64%) is produced between October and April. Snowfall comprises approximately 24% of the total annual precipitation (Figure 2.1).

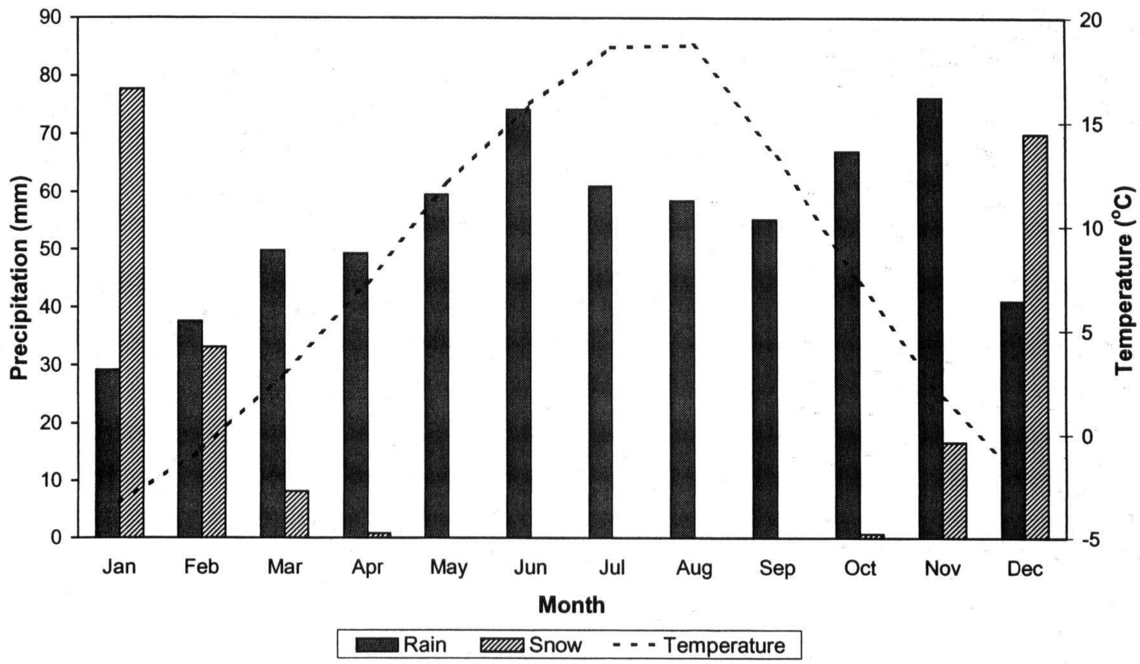

Figure 2.1. Climate normals (1961-1990) for monthly mean daily temperature, and monthly precipitation at New Denver (Slocan Valley, British Columbia).

2.1.3 Geology

The northern portion of the Slocan valley is dominated by intrusive rocks of the Kuskanax Batholith, represented predominantly by leuco-quartz monzonite, minor leucosyenite, and leucogranite. The southern half is underlain by the Nelson Batholith to the east and the metamorphosed rocks of the Valhalla Complex to the west. Rocks of the Nelson Batholith, which underlie the Ringrose Slope field site, are represented predominantly by porphyritic granites while biotite-hornblende quartz monzonite, and granodiorite monzonite are also found. The Geological Survey of Canada's Slocan map sheet (1932) identifies an eastward and upslope transition from phases of gneiss, crushed granite, and partly altered pre-batholithic rocks in the valley bottom, to mainly porphyritic crushed granite on mid-slopes immediately east of Slocan Lake and the Slocan River. The Valhalla Complex consists of low-dipping, gneiss rocks ranging in composition from granodiorite to quartzite, marble, biotite-quartz-plagioclase paragneiss and pelitic schist. A northwest trending belt (15-40 km wide) of metamorphosed volcanic and sedimentary rocks belonging to the Kaslo and Slocan Groups separates Nelson and Valhalla rocks from Kuskanax rocks. Rocks of the Nelson Batholith display greater textural and compositional heterogeneity relative to the Kuskanax Batholith and associated stocks (Ministry of Energy, Mines and Petroleum, 1981).

Surficial geology of the Slocan Valley consists of glaciofluvial deposits and alluvium in valley bottoms of the Slocan River and its major tributaries. Deep (i.e., generally >1.5 m) phases of colluvial deposits commonly accumulate at the base of slopes along the upper reaches of tributary valleys, with shallow (i.e., <1.5 m) colluvial deposits being common throughout the Slocan River watershed on steep slopes and overlying bedrock. Discontinuous basal and ablation tills occur throughout the watershed (Jungen, 1980).

2.1.4 Vegetation

The Slocan Valley lies in the Interior Cedar-Hemlock biogeoclimatic zone. Forests are composed of mixed tree species at a wide range of elevations and aspects. Englemann spruce (*Picea englemannii*) and subalpine fir (*Abies lasiocarpa*) represent the dominant species at higher elevations. At middle and lower elevations on drier sites, ponderosa pine (*Pinus ponderosa*) and Douglas-fir (*Pseudotsuga menziesii*) are the dominant tree species. Western red cedar (*Thuja plicata*), western hemlock (*Tsuga heterophylla*), western larch (*Larix occidentalis*), and western white pine (*Pinus monticola*) stands develop wherever sufficient moisture and nutrients accumulate. At middle and lower elevations and on moist aspects, mixtures of these species together with Douglas-fir are often found. Early successional tree cover includes lodgepole pine (*Pinus contorta var. latifolia*), paper birch (*Betula papyrifera*), and trembling aspen (*Populus tremuloides*) (Silva Forest Foundation, 1996).

2.2 FIELD SITE

2.2.1 Location and physiography

The research site comprised three small stream catchments on Ringrose Slope: Thickett Creek, Gurn Brook, and Gurn Spring (Figure 2.2). All three catchments share the same westerly aspect. However, catchments display varying morphologies. The presence of fracture systems in bedrock underlying the study catchments was suggested by field observations of bedrock outcrops and by the nature of the local bedrock composition and structure as identified in geologic maps (Geologic Survey of Canada, 1932).

Catchment areas were determined in ArcGIS from a digital elevation model (DEM) derived from a 1:5000 map with 5 m contour intervals supplied by Slocan Forest Products.

Uncertainty in measurement of catchment areas arose from two sources. First, subdued topography made it difficult to determine drainage divides. This was not an issue for the deeply incised and topographically distinct Gurn Brook catchment. Though not so defined as Gurn Brook, the Gurn Spring catchment is relatively well defined by topography and uncertainties in catchment area are likely small. The Thickett Creek catchment is characterized by poorly defined topography and likely possesses the largest uncertainty in drainage area from this source. This is confirmed by previous maps of the Thickett Creek catchment that showed an area greater than that of Gurn Brook. The second source of uncertainty relates to the potential for cross-catchment transfers of water along forest roads. This would yield little uncertainty with regards to estimates of Gurn Spring's catchment area due to the near absence of roads in that catchment. Conversely, field observations revealed the potential for overland flow across drainage divides along road segments in the middle and upper elevations of the Gurn Brook catchment, and lower elevations of the Thickett Creek catchment, suggesting that uncertainties in catchment areas from this source were largest in these catchments. In order to address uncertainties in catchment areas, boundaries were field-checked during both low and high flow conditions. In both cases catchment boundaries generated using the DEM were judged to provide a good representation of actual drainage divides.

Thickett Creek is composed of intermittent seeps, is weakly channelized, and surfaces approximately 10 m upslope of the weir. The Thickett Creek catchment has an estimated area of 13.7 ha at the weir, and ranges from approximately 725 m to 1445 m elevation. The Thickett Creek drainage could be characterized as a broad network of seeps and riparian zones in its lower two thirds with a small upslope contributing area.

The Gurn Brook catchment drains a broad concave slope in its upper extent, emerging into a pair of ephemeral channels that converge and flow through a deeply incised gully to the catchment outlet. The catchment is largely devoid of any riparian zone, particularly in the lower reaches. Gurn Brook is the largest of the three watersheds (57.9 ha), and ranges in elevation from approximately 650 m to 1575 m.

The Gurn Spring catchment, at 12.5 ha, is the smallest of the three. It displays a short, moderately incised channel within a broad shallow gully. A narrow riparian zone occupies the base of the shallow gully and extends the length of the stream channel. Topography of Gurn Spring's drainage area could be described as intermediate between that of the other two catchments: its channel is more incised than Thickett Creek's but not so much as Gurn Brook's, it has distinct riparian zones (though they are more limited than the broad network of seeps and riparian areas found in Thickett Creek), and it possesses moderately steep near-stream hillslopes. The Gurn Spring catchment ranges from just under 650 m to over 1075 m in elevation.

The study catchments are distinguished from other snowmelt-dominated, forested, headwater catchments in that they are small, relatively steep (slope gradients dominantly in excess of 20° or 35%), and in the case of Thickett Creek and to a lesser extent Gurn Spring, are characterized by minimal channel incision and poorly distinguished topographic boundaries. In comparison, other headwater catchments that have been the subject of snowmelt-runoff studies are characterized by lesser slope gradients and better developed channel incision and topographic boundaries. These include the 40.5 ha W9 sub-basin of the Sleepers River watershed with an average slope gradient of 13% (Kendall et al., 1999; McGlynn et al., 1999; Shanley et al., 1999; Shanley et al., 2002), and sub-catchment S of the Moshiri experimental basin (128 ha) with slope gradients in the range of 20-25% (Kobayashi, 1985; Kobayashi, 1986; Kobayashi et al., 1999). Other snowmelt-runoff studies have focussed on larger meso-scale catchments in mountainous areas (e.g. Sueker et al., 2000), on alpine catchments (e.g. Zeman and Slaymaker, 1975; Laudon and Slaymaker, 1997), on sub-arctic catchments (e.g. Spence and Woo, 2002; Spence and Woo, 2003), and on headwater catchments of relatively low relief (e.g. Moore, 1989; Maulé and Stein, 1990; Buttle and Sami, 1992; Hazlett et al., 2001).

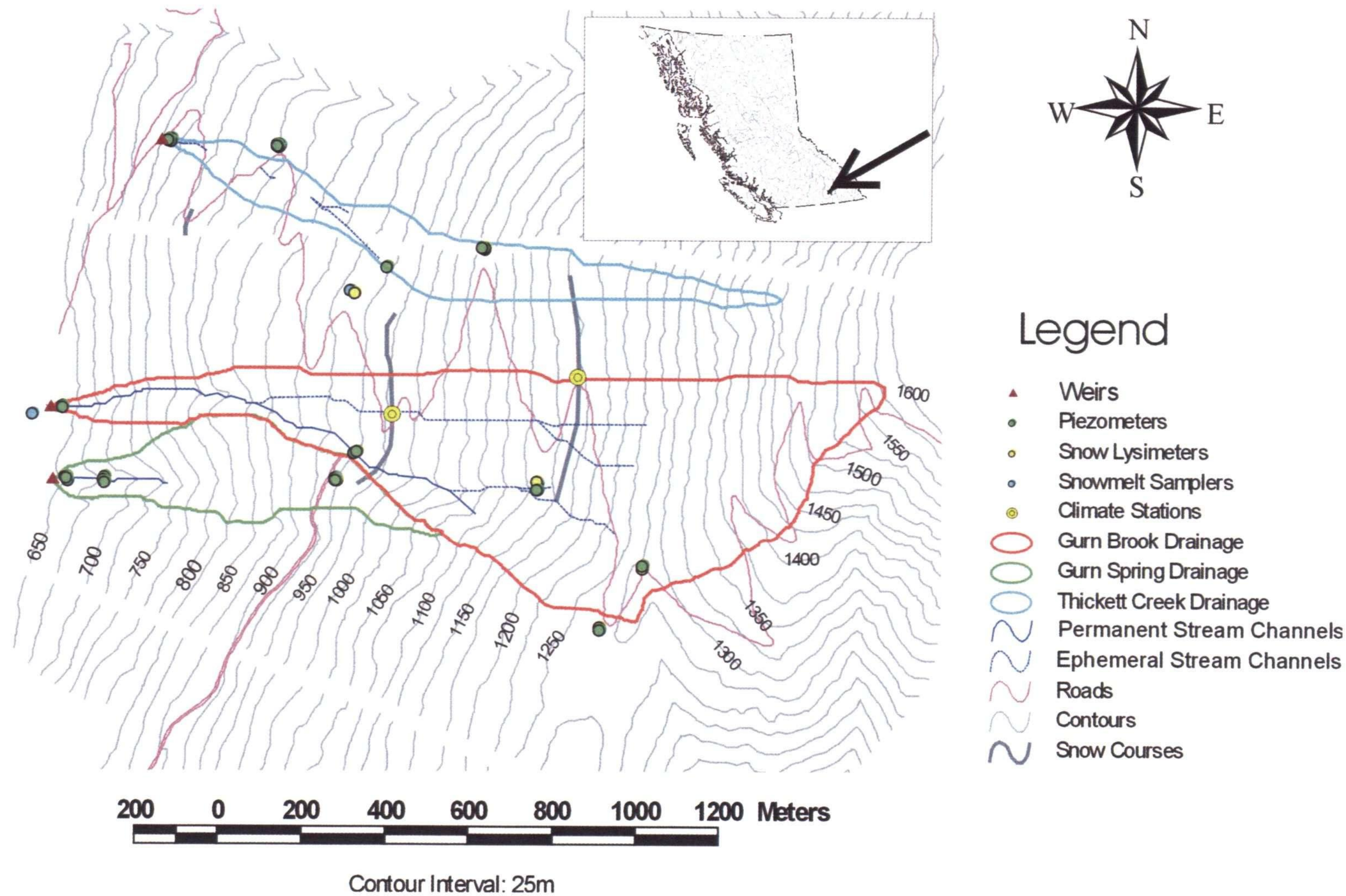

Figure 2.2. Map of the field site showing streams, catchment boundaries, instrument locations, snow courses, and access roads (instrument locations were either georeferenced using differential GPS, or estimated using pace and compass and dead reckoning).

2.2.2 *Soils*

Soils within the field site are relatively shallow (often < 1.5 m), and soil horizons tend to be poorly defined. In general, a surficial litter layer is underlain by a thin organic horizon that rests above a heavily leached mineral horizon (the organic layer becoming deeper in near-stream riparian areas). Soils display a sandy-loam texture with significant amounts of cobbles and gravels within the soil matrix. Soil characteristics observed in the field closely resemble the Bonnington Soil Association (BG) described by Jungen (1980). Bonnington soils occur on the lower slopes of major valleys, and may extend up to 1220 m on south and west aspects. BG soils are developed in loose, shallow colluvium and/or glacial till over bedrock. BG soils are dominated by the Orthic Dystric Brunisol soil sub-group, and are characterized by rapid drainage. A transition between the lower and middle valley slopes with respect to soil associations is common in the region. The soil association found on Ringrose Slope above 1200 m is likely the Buhl Creek Association (BH), one of the most common of the Nelson map area. BH soils extend to elevations of approximately 1770 m, are typically shallow (0.5-1.5 m), and are developed in shallow, loose colluvium overlying crystalline bedrock (mainly granite and granodiorite). These soils are generally well to rapidly drained (Jungen, 1980).

2.3 CLIMATE, SNOWPACK, AND STREAMFLOW DATA

Most of the data for this research were collected during the 2002 field season, which began February 11, 2002 (well before the onset of snowmelt), and proceeded until April 25, 2002 (approximately two weeks after peak flows). Additional visits were made on May 15 and 16, and June 18-20.

2.3.1 *Meteorology*

Meteorological parameters were measured at two climate stations located within the field site (Figure 2.4). The lower climate station is located at approximately 975 m while the upper station is located at approximately 1175 m. Both stations were installed in November of 1993.

Air temperature , relative humidity (Campbell Scientific temperature and RH probe model HMP 35C), and rainfall (TE525M Texus tipping bucket raingauge) were measured hourly at both stations and recorded on Campbell Scientific CR-500 dataloggers. Daily maximum, minimum, and mean air temperatures, mean relative humidity, and total precipitation were also recorded. In August of 2001, an anemometer (Met One wind speed sensor model 014A), a pyranometer (Li-cor model LI200S), and an automatic snow depth sensor (Sonic Ranging Sensor SR50) were added to the upper climate station to provide hourly measurements of wind speed, incoming solar radiation, and snow depth, respectively. Daily maximum wind speed and daily accumulated snow depth were also recorded.

2.3.2 Snow surveys

Snow depth and snow water equivalent (SWE) during the spring of 2002 were measured weekly at two snow courses maintained by the Ministry of Forests (MoF) (see Figure 2.4). The upper snow course is composed of 32 snow survey points ranging in elevation from 1150 m to 1175 m. The lower snow course is composed of 30 points at an elevation of approximately 975 m. Both snow courses have been monitored by MoF since 1988, with no snow surveys conducted in 1995, 1996, or 1997.

An additional snow course consisting of 6 snow survey points was established at an elevation of approximately 780 m during the February of 2002 to facilitate interpolation of snow depth and SWE over a broader range of elevations (see Figure 2.4). Snow depth and SWE were measured at all snow courses using a Mount Rose snow corer.

2.3.3 Snow line mapping

Following the onset of snowmelt, the snow line at the field site was mapped on a weekly basis. For mapping purposes, the "snow line" was defined as a line above which the majority of the ground surface (>50%) was covered with snow. Mapping was conducted in the field by locating the snow line at the northern extent of the field site and following it southwards on foot. Using a contour map, altimeter, and pace and compass, points along the snow line were drawn using topographic features as reference points. A total of five snow line maps were constructed showing the upslope recession of the melting front over a five-week period.

2.3.4 Streamflow

Streamflow from Thickett Creek, Gurn Brook, and Gurn Spring has been monitored since 1990 by the BC Ministry of Forests using V-notch weirs installed on each of the streams (see Figure 4). Hourly stage measurements were recorded using pressure transducers (CS400/CS405 Kellar series 169/173 as of Jan 2002, formerly Sensotec pressure transducers) attached to Campbell Scientific CR-10 dataloggers with SM4 storage modules. Weirs were equipped with stage rulers for manual stage measurements and to allow for calibration of transducer data. Stream temperature was measured hourly and recorded along with daily maximum, minimum and mean stream temperature using a 107B temperature probe connected to the dataloggers. Hourly air temperature and relative humidity was also measured at the weirs and recoded along with daily maximum, minimum, and mean air temperatures and relative humidity using a Campbell Scientific temperature and RH probe model 207.

At least twice each week, manual stage measurements were taken for each stream in both the morning and the afternoon. Electrical conductivity and stream temperature were also measured at these times using a portable WTW LF-340 conductivity probe. Once during baseflow conditions and weekly for five weeks during the spring freshet, manual stage, conductivity, and temperature measurements were made every 4 hours over a 24-hour period to investigate diurnal streamflow fluctuations.

2.4 PIEZOMETRIC DATA

A total of 30 piezometers were installed at various locations throughout the research site (Figure 4). Of these, 7 were short (<75 cm long), made of 1.5 inch PVC perforated in the lower 6 inches and wrapped in nylon mesh to prevent blockage at the intake. The others were longer (160 cm, 3 inches in diameter), prefabricated stainless steel piezometers with drive-points. All piezometers were installed by driving an iron bar into the ground to create a hole, and then driving the piezometer into the ground until either bedrock was struck or the entire piezometer (minus a few cm) was embedded. Bentonite clay was applied around the protruding end of each piezometer to prevent infiltration of surface water. Piezometers were capped with plastic bags to prevent the capture of rain or snow. Four of the piezometers (P9D, P9S, P10, and P11) were located on Ringrose Slope just north of the TH catchment. At the time of installation, these piezometers were believed to be within the catchment. Reassessment of catchment boundaries following the field season revealed these to be outside the TH catchment.

Transects of four piezometers were installed perpendicular to Thickett Creek (1 transect) and Gurn Spring (2 transects) near the weirs. Due to steep gully walls and limited access immediately above the weir on Gurn Brook, transects could not be established in this area and 2 piezometers were located next to the stream in the gully bottom. An attempt was made to locate the remaining piezometers at representative hydrogeomorphic positions throughout the catchments (e.g., near-stream riparian areas, near-stream hillslopes, upslope contributing areas). Wherever piezometers were installed in riparian areas, short piezometers were paired with the longer stainless steel piezometers in order to estimate a vertical hydraulic gradient, and to sample shallow and deep soil water for chemical analysis. At all other locations, the longer stainless steel piezometers were used in order to penetrate as deeply as possible. Water levels in all piezometers were measured manually at least once per week. Crest stage gauges constructed from rigid transparent plastic tubes containing Styrofoam "floats" were inserted into piezometers, thereby providing a means of measuring maximum water levels between visits. Two piezometers were equipped with pressure transducers attached to Campbell Scientific CR-10X dataloggers to provide water level measurements at 10 minute intervals.

2.5 Field Observations of Surface Flow

Throughout the field season the locations and timing of surface flow were recorded whenever it was observed within the study site. Surface flow was intensively monitored immediately following peak flows and field sketch maps of surface flow locations were created over the period April 15-18. Points were plotted on field maps and flagged in the field with high visibility tape wherever surface flow either:

1. Commenced on the road due to interception from adjacent cut-banks,
2. Left the road either due to infiltration into the road-bed or as a result of diversion off of the road, or
3. Was observed in other areas not on the road (e.g. seepage observed at the base of forested hillslopes or SOF observed in riparian zones).

In order to investigate the extent to which the road influenced drainage patterns, an attempt was made to estimate the proportions of surface flow continuing along the road and diverted off of the road for each point plotted along the road on field maps. Observation points were re-visited on Apr 22-24, 2002 and May 15-16, 2002. On these dates each point was listed as being either active (i.e. surface flow persisted) or inactive (i.e. no surface flow observed) and proportions of flow diverted from active locations were again estimated.

Surface flow observed elsewhere was mapped in order to record the extent to which SOF occurred within the study catchments. These points were also re-visited on the dates stated above, and were listed as either active or inactive.

2.6 WATER CHEMISTRY

2.6.1 Streamwater

Streamflow samples were collected at least twice weekly for analysis of oxygen-18, major cations (Ca, Mg, K, Na), and silica (Si). Twice-weekly samples for analysis of dissolved organic carbon (DOC) were collected during the three weeks straddling peak flows. Once during baseflow conditions and weekly for five weeks during the spring freshet, water samples were collected for analysis of oxygen-18 and water chemistry every 4 hours over a 24-hour period to investigate diurnal fluctuations in stream chemistry. All streamwater samples were collected manually at the weirs using polyethylene sampling bottles. All bottles received a minimum of two rinses prior to sample collection. Streamwater electrical conductivity (EC) and temperature were measured in the field at each sampling time.

2.6.2 Melt and rainwater

Meltwater samples were collected from 8 sampling trays inserted into the base of the snowpack at various locations within the field site. Sampling trays were constructed using flat-bottomed plastic bins, approximately 0.5 m wide, 1 m long, and 0.25 m deep. The back end of each bin was cut away leaving three sides and a bottom, thereby allowing the sampling tray to be manually inserted at the base of the vertical profile of the snowpack. Sampling bottles were then placed under a drain hole located at the front of the sampling tray to collect composite samples of melt and rain water. The date and time each bottle was placed was recorded, and bottles were then observed daily and collected when at least 100-200 mL of water had accumulated (again recording date and time of sample collection). Samples were then analyzed for oxygen-18. To avoid changes in isotopic signatures due to evaporation, a thin film of oil was added to each bottle at the time of its placement, thereby sealing accumulated melt/rainwater from interaction with the atmosphere. Upon retreat of the snow-line above the sampling trays, they continued to be used as rain water collectors following the same procedure.

2.6.3 Piezometers

Up to three subsurface water samples were collected from each piezometer (Feb. 11-13, May 15, and June 18). Samples were collected as follows:

1. The piezometer was purged and allowed to refill.

2. Using a handheld Nalgene vacuum pump connected to a length of Nalgene tubing and polyethelene collection bottle, water was extracted and used to rinse the sampling apparatus (this rinsing process was repeated twice prior to sample collection).
3. The sample was extracted into the collection bottle and transferred to 125 mL polyethelene storage bottles (each receiving a minimum of two rinses prior to filling with sample). These were then labelled and stored according to laboratory-recommended protocols.

Subsurface water samples were analyzed for oxygen-18, the major cations, and silica. Temperature and EC were measured in the field at each sampling time.

2.6.4 Overland flow

Overland flow samples were collected on an opportunistic basis, primarily from surface flow along the deactivated access road. Samples were collected manually using polyethylene sampling bottles. Each bottle was rinsed at least twice prior to sample collection. All overland flow samples were submitted for analysis of oxygen-18, the major cations, silica, and DOC. Temperature and EC were measured in the field.

2.7 LABORATORY ANALYSIS

2.7.1 Oxygen-18

Oxygen-18 (^{18}O) was analyzed by means of mass spectrometry at the Stable Isotopes Laboratory of the National Water Research Institute in Saskatoon, SK. The ratio of the heavier ^{18}O to the ^{16}O isotope, referenced against its deviation from the ratio in 'standard mean ocean water' (SMOW), is used to express the abundance of stable isotopes in a water sample, and is denoted as follows:

$$\delta^{18}O = [(R_{sample} - R_{SMOW})/R_{SMOW}] \cdot 1000 \quad (1)$$

where $\delta^{18}O$ = the relative difference in the ratios in units of parts per thousand (per mil), R_{sample} and R_{SMOW} = the ratios of ^{18}O to ^{16}O in the water sample or in SMOW, respectively (Buttle, 1994). The analytical precision of the method was ±0.2 per mil. A number of blank samples were re-submitted to the laboratory for QA/QC purposes. All ^{18}O samples were stored in cool and dark conditions prior to analysis.

2.7.2 Hydrochemistry

Concentrations of the major cations (Ca, Mg, Na, and K) and silica (Si) were measured by inductively coupled plasma mass spectrometry (ICP-MS) at the University of British Columbia's Soil Resources Laboratories. Concentrations were reported in milligrams per litre (mg/L). All water samples were pre-filtered in the field using glass-fibre filter papers (<0.2 micrometer pore size) to remove any suspended solids.

2.7.3 Dissolved organic carbon

Concentrations of non-purgeable dissolved organic carbon (DOC) were measured at the Environmental Sciences Laboratories of Okanagan University College, Kelowna, British Columbia. All DOC samples were pre-filtered in the field using Watman GF-C glass fibre filter papers. All filter papers were muffled before use in the field (i.e. heated at 450 °C for approximately 2 hours to remove trace amounts of carbon).

2.8 DATA ANALYSIS

2.8.1 Analysis of peak flow generating mechanisms

Peak flow generating mechanisms (i.e. snowmelt, rain-on-snow, or rainfall) were determined for each stream catchment by considering the SWE at the time of peak flows and inspecting rainfall and air temperature data collected during the week immediately prior to peak flows.

2.8.2 Inter-catchment comparison of diurnal streamflow response

Data from published research papers was used to compare diurnal streamflow response observed in the three study catchments with that observed in other headwater catchments. The aim was to find data for as many different snowmelt-dominated headwater catchments as possible from published material. The following criteria were used to select studies for this meta-analysis:

1. The study catchment is small (i.e., not exceeding 1.5 km^2 in area), predominantly forested, and is snowmelt-dominated or received significant water inputs as a result of snowmelt.
2. Information regarding snowpack water equivalent (SWE) prior to melt is provided.
3. Information regarding catchment area and elevation range is included.

4. Rainfall data are provided for the period of interest (i.e., melt season).
5. A streamflow hydrograph presenting diurnal fluctuations is presented for the period of interest (i.e., melt season).

A non-dimensional index of catchment steepness (S*) known as the Melton ruggedness index (Melton, 1965) was computed as:

$$S^* = (H_{max} - H_{min})/A^{0.5} \tag{2}$$

where H_{max} and H_{min} are the maximum and minimum elevations of the catchment, respectively, and A is the catchment area.

A measure of each catchment's diurnal streamflow response that would allow for direct comparison between catchments was computed as:

$$DR = (Q_{max} - Q_{min})/Q_{min} \tag{3}$$

where DR is a unitless measure of catchment diurnal streamflow response, and Q_{max} and Q_{min} are the maximum and minimum discharges recorded on a given day, respectively.

DR was calculated for each catchment for the day showing the largest diurnal variation over a period of no more than 10 days before or after the date of peak flow. Days on which rainfall was recorded were excluded. For consistency, diurnal variation was measured from minimum to maximum daily discharge on either the rising or falling limb of the peak flow hydrograph (Figure 2.3). Where more than one year of data was available for a given catchment, the mean DR was used to represent the catchment's diurnal response index.

In the case of data from published research papers, daily minimum and maximum discharge was measured directly from printed hydrographs. Similarly, where no value was expressly stated for maximum pre-melt SWE, it was estimated from printed time series graphs of SWE. For the three study catchments (Thickett Creek, Gurn Brook, Gurn Spring) and Upper Redfish Creek, daily minimum and maximum discharge and antecedent SWE was taken from hourly discharge data and digital snow survey data. The accuracy of the measurement technique was estimated by printing hydrographs from the digital datasets and comparing the raw data with estimates derived from printed hydrographs (as per the method described above). Estimated daily maximum and minimum discharge measured from printed hydrographs differed from the raw data by less than 1% on average.

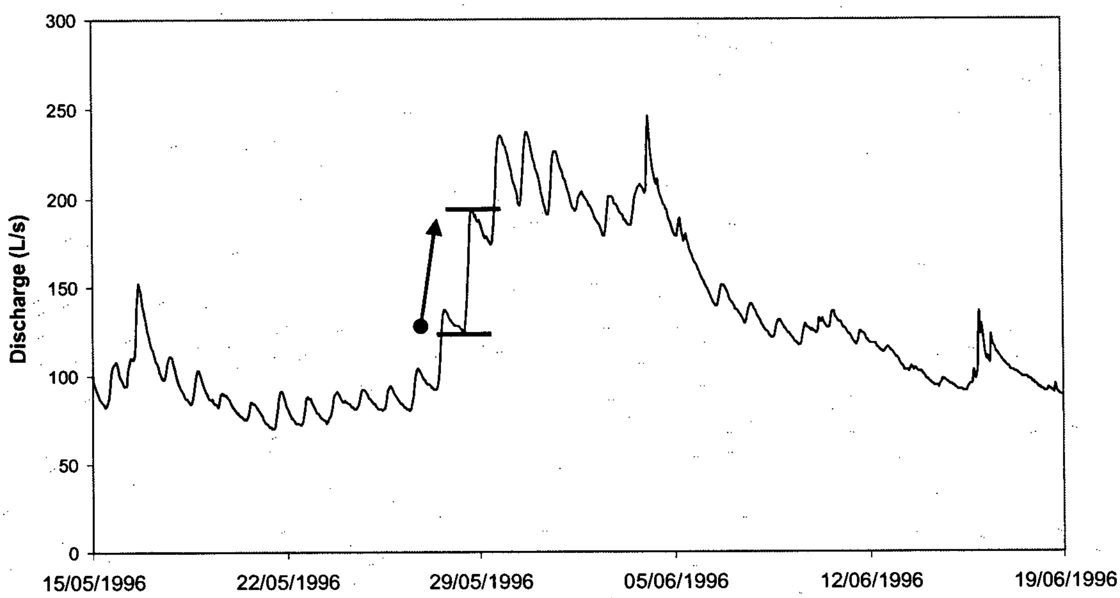

Figure 2.3. Example of a peak flow hydrograph illustrating the method used for measuring daily streamflow variation. Daily variation was measured from daily minimum to maximum discharge.

A thorough search of published literature yielded 11 catchments (including the study catchments) that met the selection criteria. Two years of data were used for two of these catchments (Moshiri Experimental Basin and Redfish Creek). For the three study catchments (Thickett Creek, Gurn Brook, and Gurn Spring), four years of data were used. A single year of data was available for each of the remaining catchments (i.e., Sleepers River Watershed "W-9", Hermine Basin, and Woods Lake Watersheds "WO2" and "WO4").

2.8.3 *Statistical analysis of ^{18}O inputs*

Spearman correlation analysis was performed to test whether systematic temporal and/or spatial patterns among the concentrations of ^{18}O in meltwater inputs existed. To test whether a temporal pattern existed, meltwater ^{18}O data were stratified according to the elevation of meltwater samplers (i.e. isolating all samples collected from one elevation/sampler). To test whether a spatial (i.e. elevational) pattern existed, meltwater ^{18}O data were stratified by date (i.e. isolating all samples collected on a given date or sequence of dates. The use of Spearman's rank-based correlation test requires no assumptions about the probability distributions underlying the data, and can also accommodate nonlinear relations. Observed patterns and/or lack thereof were displayed using scatterplots generated from the selected data and fitted with LOWESS trendlines.

2.8.4 Principal components analysis of streamwater chemistry

Principal components analysis (PCA) was performed on streamwater chemistry data. Factors with eigenvalues greater than 1.0 were identified as being "significant" (Hair et al., 1995). PCA's were performed separately for each stream using the following variables: Si, DOC, the ratio (Na+K)/(Na+K+Ca+Mg) ($R_{Na\text{-}K}$) and EC. Silica has been employed as an indicator of runoff contributions from deep subsurface waters characterized by a relatively long contact time (Maulé and Stein, 1990; Buttle and Sami, 1997; Ladouche et al., 2001), and the EC of subsurface waters has been shown to increase with depth (Kobayashi, et al. 1999). Dissolved organic carbon has been used as an indicator of surface flow or flow through shallow saturated soil horizons (McGlynn et al., 1999; Ladouche et al., 2001). $R_{Na\text{-}K}$ is commonly employed in Piper's Diagrams to describe subsurface water chemistry (Freeze and Cheery, 1979), and was used as a means of collapsing cation concentrations into a single parameter. Spearman correlation analysis showed that $R_{Na\text{-}K}$ and DOC concentrations in streamwater samples collected during the field season were strongly related ($p < 0.005$, $n = 89$), suggesting that in this study $R_{Na\text{-}K}$ could be used as an indicator of surface/shallow subsurface flow.

A separate PCA was conducted for Ringrose Slope using all streamwater, piezometer, and overland flow samples collected during the field season. The PCA was run using the same four parameters described above. Results of this PCA are intended to describe factors responsible for the observed variance in the chemistry of all waters sampled from Ringrose Slope, and particularly to explore chemical contrasts among the streams.

CHAPTER 3
RESULTS

This chapter draws upon streamflow, snowpack, and meteorological data collected over several years as well as detailed measurements for one field season. The detailed field study was conducted during the winter and spring of 2002, beginning on February 8, 2002, well before the onset of snowmelt, and continuing until April 25, 2002. Two further visits were made to the field site on May 15-16 and June 18-20 respectively. Sections 3.1 and 3.2 provide a context for the field season by presenting results of snowpack, climatic and streamflow measurements collected over a number of years and for the detailed field season. Sections 3.3 and 3.4 present results of piezometer measurements and observations of overland flow collected during the field season. Section 3.5 addresses the temporal and spatial variation in isotopic concentrations of melt and rainwater. Section 3.6 contains results of analyses of water chemistry, and 3.7 presents results of the isotopic hydrograph separation.

3.1 Overview of the Study Period

The timing and magnitude of peak SWE varied substantially amongst years (Figure 3.1). The peak snow accumulation at 975 m was high in 2002 compared to previous years, and the melt season began relatively late. At 1175 m, the peak snow accumulation and timing of melt appeared to be intermediate compared to previous years. The main snowmelt period began about March 19, when air temperatures jumped above 0°C, and streamflow peaked on April 14 for all three streams (Figure 3.2). Air temperatures measured during the 2002 field season were low relative to previous years, while maximum daily and total monthly rainfall were average relative to previous years (Table 3.1).

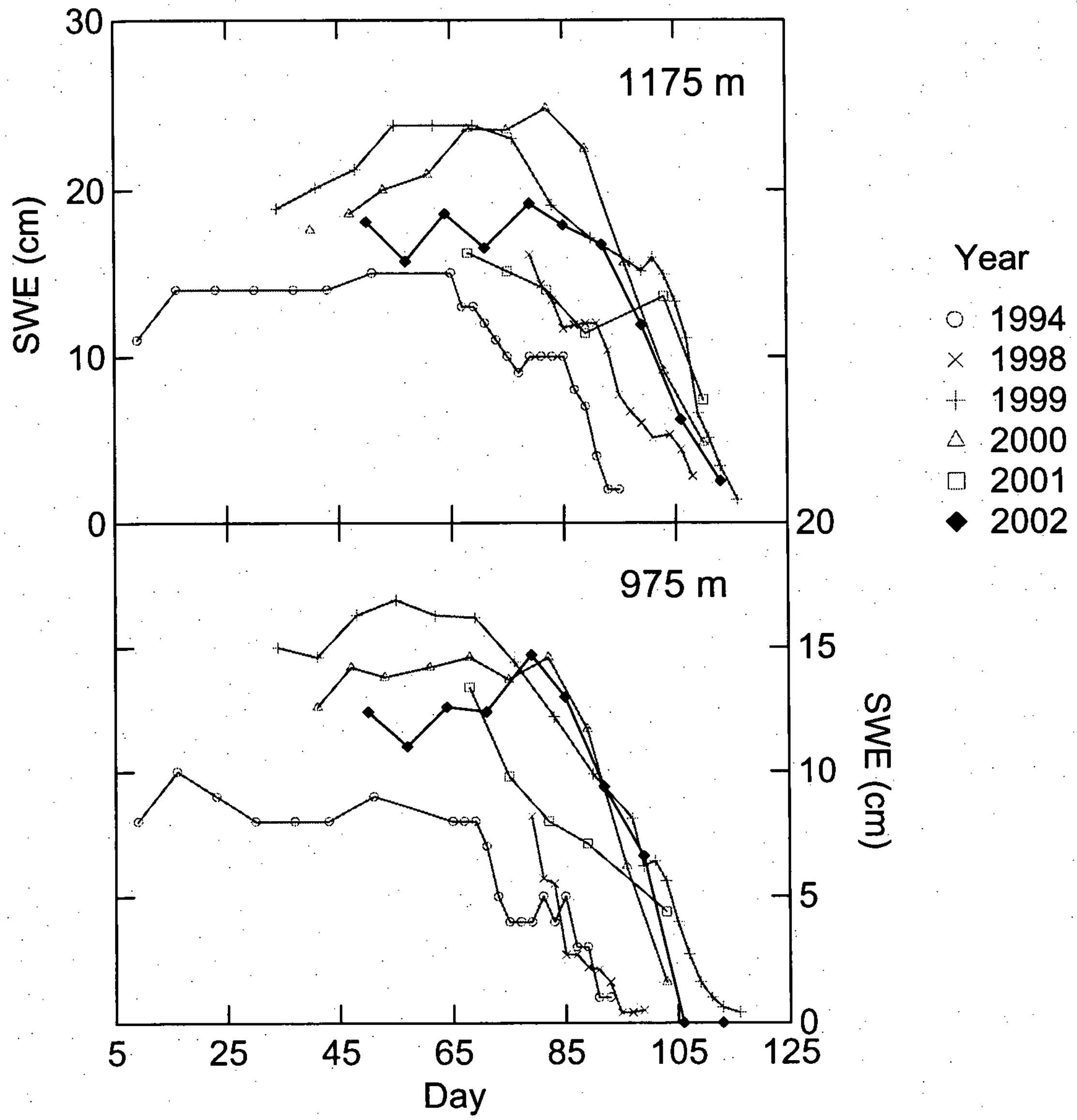

Figure 3.1. Snow water equivalents measured in forested areas at 1175 m and 975 m on Ringrose Slope. SWE measured during the field season is shown in black.

Table 3.1. Daily air temperature and rainfall data collected from 1175 m and 975 m on Ringrose Slope during the freshet season for several years on record. Data collected during the field season is included for comparrison.

		1995			1996			1999			2000			2001			2002		
		Mar	Apr	May	Mar	Apr	May	Mar	Apr	May	Mar	Apr	May	Mar	Apr	May	Mar	Apr	May
Daily Air Temp @ 1175 m (°C)	Mean	0.3	4.1	11.7	-0.3	4.4	6.5	-0.1	3.7	7.3	0.4	4.3	7.7	0.7	2.8	9.6	-3.1	3.3	7.1
	Max	6.4	8.1	20.5	5	8.9	14.1	5.3	10	18.4	4.0	8.7	13.2	4.0	9.6	20.8	4.7	9.2	12.6
	Min	-8.9	0	6.1	-6.1	0.9	0.8	-3.9	-0.7	0.2	-2.6	-1.2	1.6	-2.9	-1.1	1.6	-11.3	-0.7	-0.6
Daily Air Temp @ 975 m (°C)	Mean	1.4	5.2	12.5	0.3	5.4	7.6	1.0	5.4	8.9	1.5	5.8	9.2	1.6	4.4	11.1	-1.9	4.7	8.4
	Max	6.9	9.2	20.3	4.7	9.8	15.0	6.2	12.4	19.2	4.3	10.7	14.8	4.6	12.0	21.1	5.6	11.3	13.4
	Min	-8.0	1.6	7.7	-5.6	1.7	1.8	-2.6	1.0	2.1	-0.8	0.1	3.2	-1.8	0.3	3.1	-9.5	0.6	0.8
Daily Rainfall @ 1175 m (mm)	Max	33.5	9	5.5	9.5*	32*	19	18.7	24.7	15.6	11.7	8.9	0	9.9	22.7	8.9	18.1	13.1	10.7
	Total	129.5	48	23	37*	75.5*	123	26.3	92	50.1	51.7	16.9	0	67.7	75.9	45.9	70	46.6	43.9
Daily Rainfall @ 975 m (mm)	Max	28.5	6.5	4.5	8.5	26.5	18	17.7	8.8	15.2	11.4	24.7	13.7	10.8	22	9.8	8.9	11.6	19.5
	Total	118	42	15	44	104	112	82	37.5	52.1	81.6	113.7	48.3	68.9	70	43.1	65.9	41.8	89

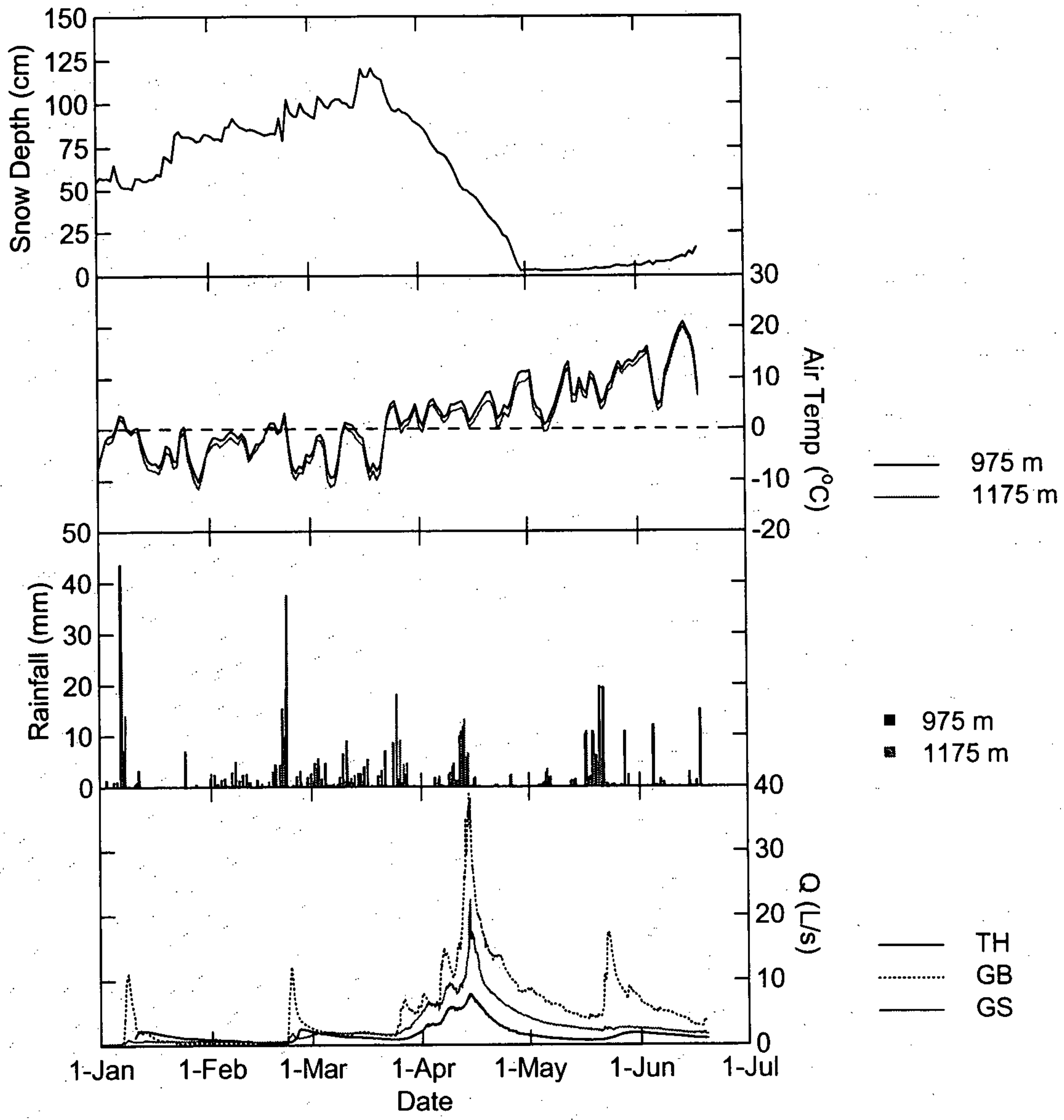

Figure 3.2. Overview of the field season. From top to bottom, time series of snow depth at 1175 m, mean daily air temperatures, daily rainfall, and streamflow from each of the three stream catchments during the spring 2002 field season.

The snow line began to recede above the weirs on Gurn Brook and Gurn Spring during the week of March 26, and above the weir on Thickett Creek during the week of April 4 (Figure 3.3). Snow lines drawn on April 10 and 18 bracket the time of peak flows recorded on all streams. By April 18, almost 100% of the snow had melted off Gurn Spring. On April 24, roughly 17% and 55% of the Thickett Creek and Gurn Brook catchments remained snow covered. Upon return to the field site on May 15, all snow cover had melted from the slope.
Peak flows occurred on April 14 for all three streams and were preceded by rise in air temperatures and moderate rainfall onto partial snow cover. Gurn Brook and Thickett Creek experienced the highest and lowest flows, respectively (Table 3.2). At the time of peak flows, snow depth at the upper climate station was 50.1 cm.

3.2 STREAMFLOW VARIABILITY

This section presents results of streamflow data analysis. Section 3.2 compares peak flows and unit runoffs from a number of years, while section 3.2.2 examines diurnal streamflow variability at the three study streams. A comparison between the diurnal streamflow response at the study catchments and that observed in other published studies is presented in section 3.2.3.

3.2.1 Comparison of streamflow amongst the three streams

Streamflow was highly variable amongst years for all three streams (Figure 3.4). Gurn Brook consistently displayed the flashiest response of the three streams, while Thickett Creek showed the most subdued streamflow.

For all years, the GS catchment produced the largest unit runoff, while the TH and GB catchments produced similar unit runoffs (Figure 3.5). Unit runoffs for all streams in 2002 were relatively low compared with those of previous years.

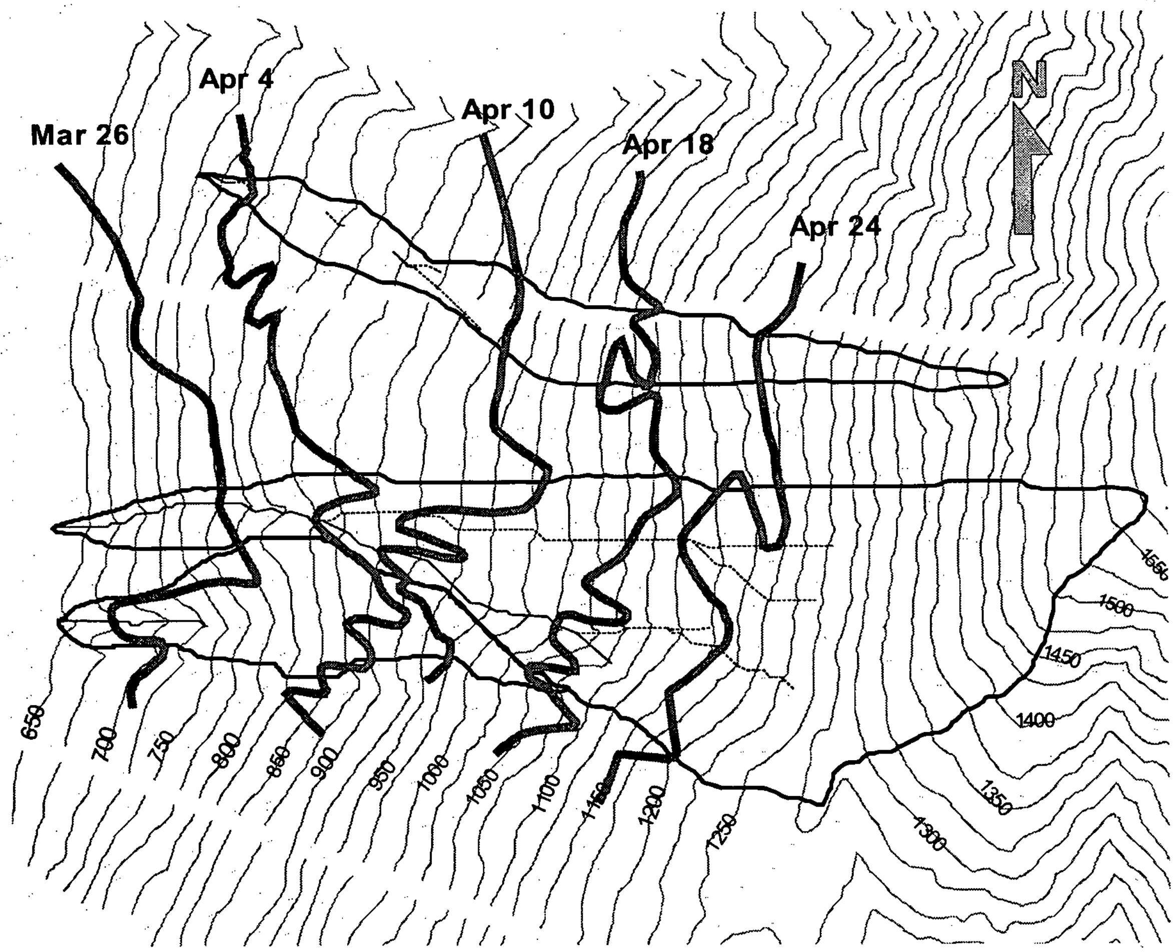

Figure 3.3. Snow line position on Ringrose Slope during the spring 2002 field season.

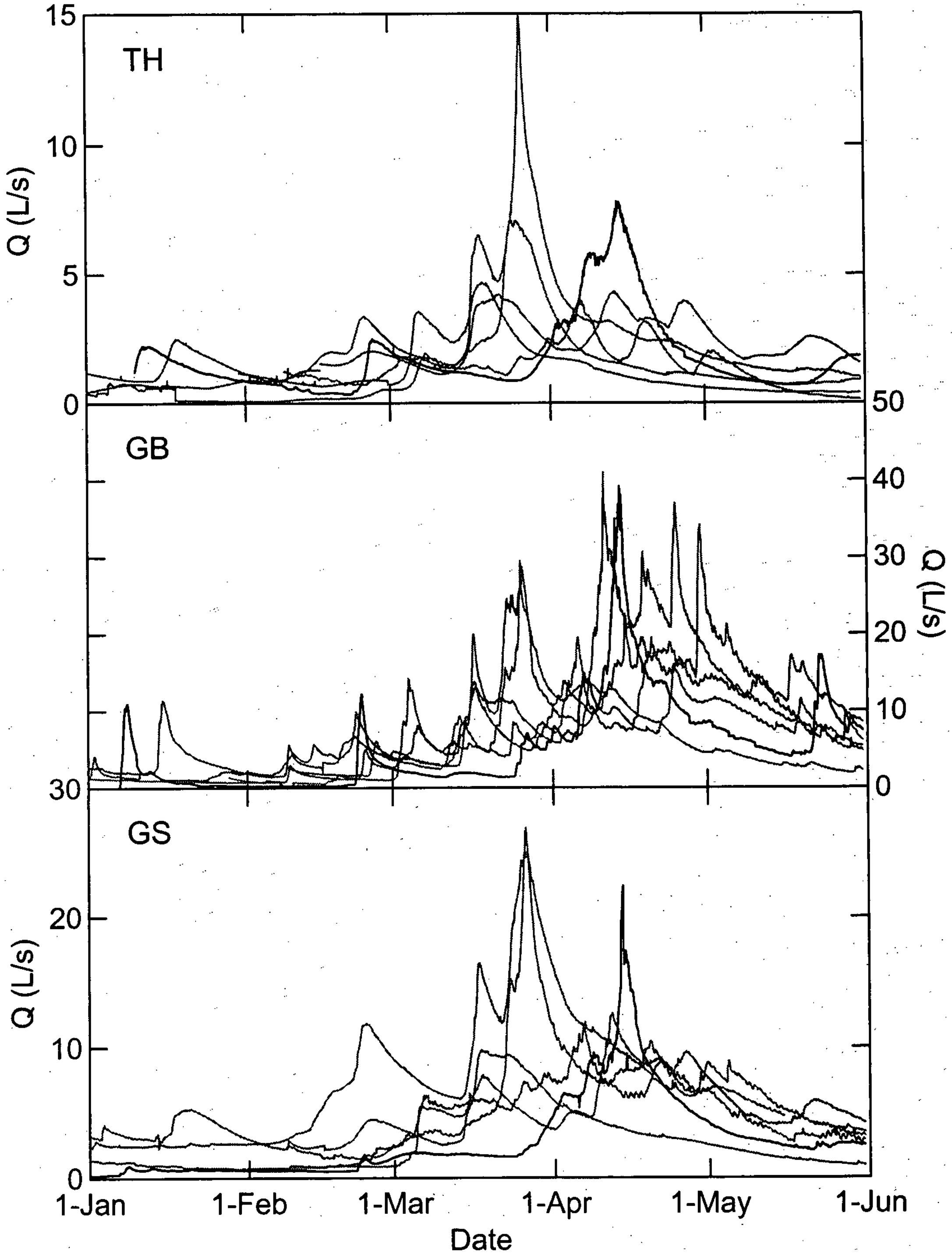

Figure 3.4. Freshet hydrographs for Thickett Creek (TH), Gurn Brook (GB) and Gurn Spring (GS) for several years on record. The detailed field season is shown in black for comparison.

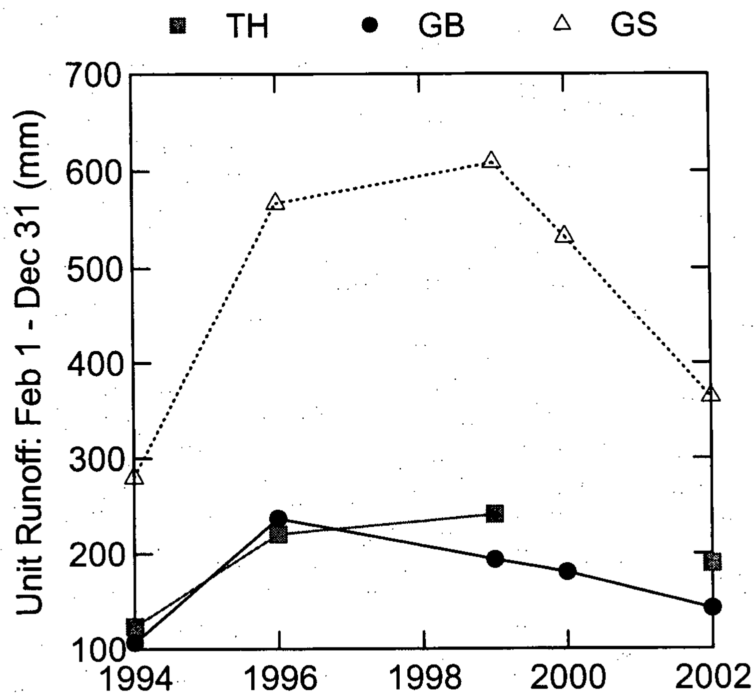

Figure 3.5. Inter-annual variation in unit runoff (mm).

Table 3.2. Timing of peak flows in relation to snow water equivalents for selected years on record. Along both snow courses, only measurements at forested survey points were included in the average. No snow survey data was available for the years 1995 and 1996.

Year	Stream Catchment	Date and Time of Peak Flow	Peak Flow (L/s)	Peak Flow ($Ls^{-1}ha^{-1}$)	SWE at 975m at Time of Peak Flows (mm)	SWE at 1175m at Time of Peak Flows (mm)	Peak Flow Generated By:
1994	TH	Mar. 18 (20:00)	4.7	0.34	40	90	ROS
	GB	Mar. 4 (04:00)	14.2	0.25	80	150	ROS
	GS	Mar. 18 (01:00)	7.9	0.63	40	90	ROS
1995	TH	Mar. 15 (18:00)	9.2	0.67	-	-	-
	GB	Mar. 15 (14:00)	53.5	0.92	-	-	-
	GS	Mar. 16 (6:00)	20.9	1.67	-	-	-
1996	TH	Apr. 12 (16:00	4.3	0.31	-	-	-
	GB	Apr. 10 (2:00)	41.0	0.71	-	-	-
	GS	Apr. 11 (6:00)	12.6	1.01	-	-	-
1998	TH	Mar. 25 (11:00)	7.1	0.52	41	125	ROS
	GB	Mar. 25 (22:00)	26.2	0.45	41	125	ROS
	GS	Mar. 26 (18:00)	25.0	2	27	117	ROS
1999	TH	Mar. 26 (07:00)	14.9	1.09	115	185	ROS
	GB	Mar. 25 (19:00)	29.6	0.51	119	188	ROS
	GS	Mar. 26 (18:00)	26.9	2.15	115	185	ROS
2000	TH	Apr. 5 (18:00)	4.0	0.29	62	156	ROS
	GB	Apr. 28 (19:00)	34.2	0.59	0	0	Rainfall
	GS	Apr. 5 (17:00)	11.6	0.93	62	156	ROS
2002	TH	Apr. 14 (03:00)	7.8	0.57	19	92	ROS
	GB	Apr. 14 (05:00)	39.2	0.68	19	92	ROS
	GS	Apr. 14 (11:00)	22.4	1.8	19	92	ROS (rainfall)*

* See discussion below.

3.2.2 Timing and magnitude of peak flows

Peak flows on Thickett Creek, Gurn Brook, and Gurn Spring occurred within 8 hours of each other on April 14, 2002, with Thickett Creek and Gurn Spring peaking first and last, respectively (Table 3.2). At the time of peak flows, the snow line elevation within the TH, GB, and GS catchments was approximately 1000 m. The proportion of snow covered area remaining within the TH, GB, and GS catchments was approximately 52%, 80%, and 5% respectively, and SWE measured in forested areas at 1175 m (where snow cover persisted) was approximately 92 mm.

Gurn Brook experienced the highest absolute peak flows, followed by Gurn Spring and Thickett Creek (Table 3.2). However, Gurn Spring had the highest unit peak flows. Peak flows in 2002 were relatively high (lower only than 1995 and 1996) and occurred late in the season relative to previous years. Hydrographs generated from hourly streamflow data for all years on record are presented in Appendix A.

Peak flows for each of the catchments generally occurred within 1-2 days of each other in most years, with the exception of 1994 and 2000, when peak flows at Gurn Brook occurred well before (1994) and after (2000) peak flows for the other catchments in response to large rain events. Rain-on-snow (ROS) was judged to be the dominant mechanism for generating peak flows on all streams. The single exception occurred in 2000, when peak discharge from Gurn Brook occurred in response to a rainfall event after the snow cover had receded above the upper snow course at 1175 m. Lack of snow survey data prevented evaluation of peak flow generating mechanisms for the years 1995 and 1996.

Weekly snowline maps drawn during the 2002 field season, however, call the preceding conclusion into question. Figure 3.3 clearly shows that nearly no snow cover remained in the Gurn Spring catchment at the time of the peak flows (April 14, 2002). This is likely the result of: (a) Gurn Spring's lower elevation relative to the other two study catchments, and (b) the pattern of melt followed by the snow line as it receded upslope. The conclusions drawn from the preceding analysis of peak flows must be qualified. In particular, peak flows on Gurn Spring in the year 2002 appear not to have been generated as a result of ROS as originally concluded, but rather in response to rainfall.

Snowline maps were not available for any year except 2002. As a result, conclusions regarding peak flow generating mechanisms for the remaining four years could not be checked. A further limitation involved with assigning peak flow generating mechanisms without the aid of snowline maps is that a significant proportion of the area of the Gurn Brook catchment lies above the elevation of the upper snow course (1175 m). As a result, it may be that an SWE of zero measured at 1175 m does not necessarily indicate that little or no snow remains within the Gurn Brook catchment.

The dominant peak flow generating mechanisms assigned to Gurn Spring for the years 1994, 1998, 1999, and 2000, and to Gurn Brook for the year 2000 in Table 3.2 are thus qualified.

3.2.3 Diurnal streamflow variability

Hourly streamflow from each of the streams was plotted for three 6-day dry periods immediately preceding peak flows for the years 1999, 2000, and 2002, in order to examine diurnal streamflow variation resulting from snowmelt alone (Figure 3.6). A clear diurnal response was observed in Gurn Brook for 1999 and 2000, and in Gurn Spring for 1999. No clear diurnal response was seen in Gurn Spring for 2000 and 2002, and the diurnal fluctuation in Gurn Brook streamflow during 2002 was marginal at best. A distinct lack of diurnal streamflow fluctuation was observed in Thickett Creek for each year shown. Snow cover remained on all three catchments during the periods shown (Table 3.2). Snowline maps drawn during the 2002 field season show the snow line rapidly receding upslope during the period shown, indicating ripe snowpack conditions at lower elevations (Figure 3.3). Consequently, a systematic diurnal pattern was expected.

When compared to other catchments reported in the literature, Thickett Creek, Gurn Brook, and Gurn Spring displayed the lowest diurnal streamflow responses despite being the steepest of the catchments surveyed. Spearman correlation analysis revealed a significant inverse relation between S* and DR ($r_s = -0.785$, $p < 0.005$, $n=12$).

Table 3.3. Comparison of diurnal hydrograph responses during snowmelt (S* = index of catchment steepness, DR = index of diurnal response).

Catchment Name	Area (ha)	S*	DR	Reference
Moshiri Exp. Basin "S"	128.0	0.22	0.65	Kobayashi (1985,1986)
Moshiri Exp. Basin "S"	128.0	0.22	1.06	Kobayashi (1999)
Redfish Upper Basin	115.0	0.76	0.26	Unpublished data, BC MoF
Sleepers River Watershed "W-9"	40.5	0.24	0.12	Shanley et al. (2002)
Perch Lake Watershed "3"	3.1	0.08	0.38	Buttle and Sami (1992)
Hermine Basin,	5.3	0.13	3.00	Moore (1989)
Woods Lake Watershed "WO2"	41.3	0.16	1.74	Burns and McDonnell (1998)
Woods Lake Watershed "WO4"	61.2	0.15	1.73	"
Gray Creek Catchment	149.5	0.20	1.00	Kim et al., (in press)
Thickett Creek	13.7	1.95	0.08	This study
Gurn Brook	57.9	1.22	0.14	"
Gurn Spring	12.5	1.20	0.02	"

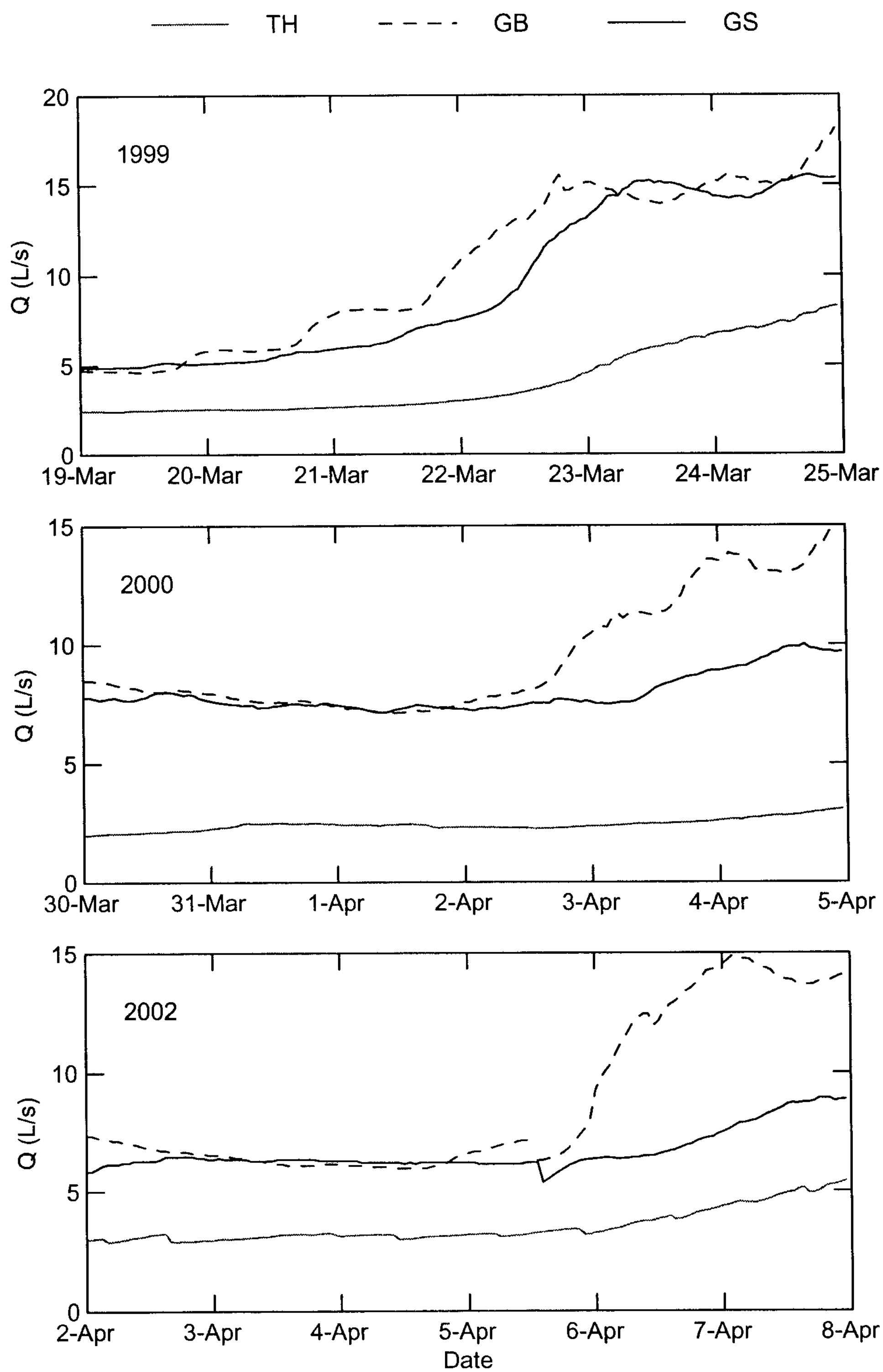

Figure 3.6. Diurnal streamflow variability during three 6-day dry periods preceding peak flows for the years 1999, 2000, and 2002.

3.3 Piezometer Data

This section presents results of piezometer data collected during the field season. Section 3.3.1 presents piezometer water level variations through time, while section 3.3.2 examines the distribution of maximum recorded water levels in piezometers during the field season.

3.3.1 Time series of piezometer water levels

Time series plots of water level and crest data collected from all piezometers are presented in Appendix B. Three examples, one selected from each of these hydrogeomorphic positions (near-stream riparian areas (NSRIP), near-stream hillslopes (NSHIL), and upslope contributing areas (UP) are presented in Figure 3.7. Water levels at P2 varied little throughout the field season, while P19 showed some response over time. Of the three piezometers represented, only P17 exhibited a water level variation corresponding to streamflow variation. Time series plots of water level and crest data for the remaining piezometers generally support these patterns (Appendix B).

Figure 3.7 also shows continuously recorded water level data from two piezometers, P3d and A1. P3d is located at approximately 1135 m within the Gurn Brook catchment, next to an ephemeral tributary of Gurn Brook in an area of convergent hillslopes. A1 is located at approximately 940 m elevation within the Thickett Creek catchment. Water levels in P3D peaked approximately 19.5 hours after the end of the rainfall, while streamflow in Gurn Brook (measured at the weir) peaked another 2.5 hours after this. Water levels in A1 peaked approximately 30.5 hours after the end of the rainfall, while streamflow in Thickett Creek peaked another 49.5 hours after this.

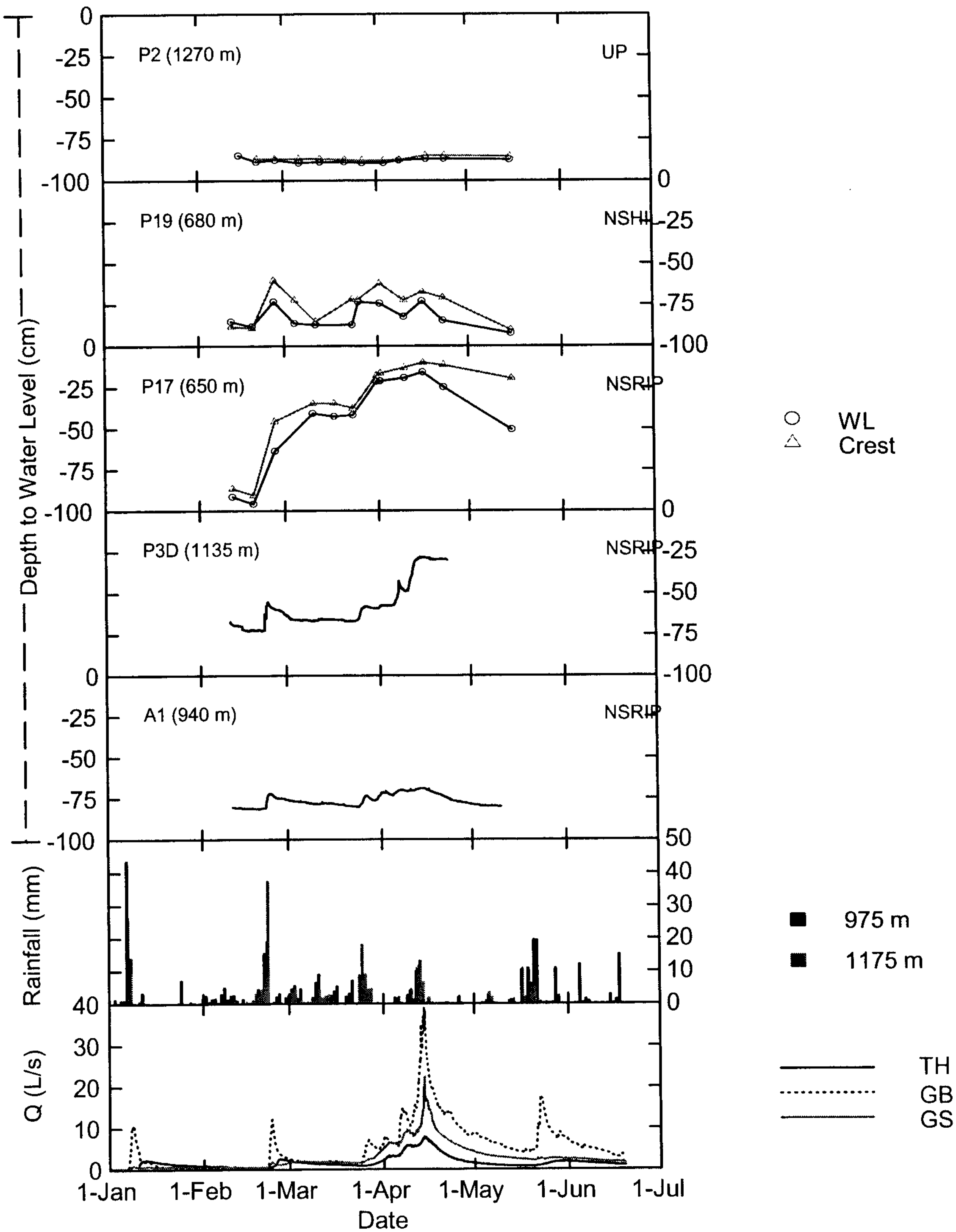

Figure 3.7. Water levels and crests measured in piezometers in relation to rainfall and streamflow. Data are shown for P2 (GB), P19 (GS) and P17 (GS), automatically recorded water levels piezometers P3D (GB) and A1 (TH). Hydrogeomorphic positions for each piezometer location are shown in the top-right of each plot. Elevations are shown in parentheses. Water levels are expressed as elevations relative to the soil surface.

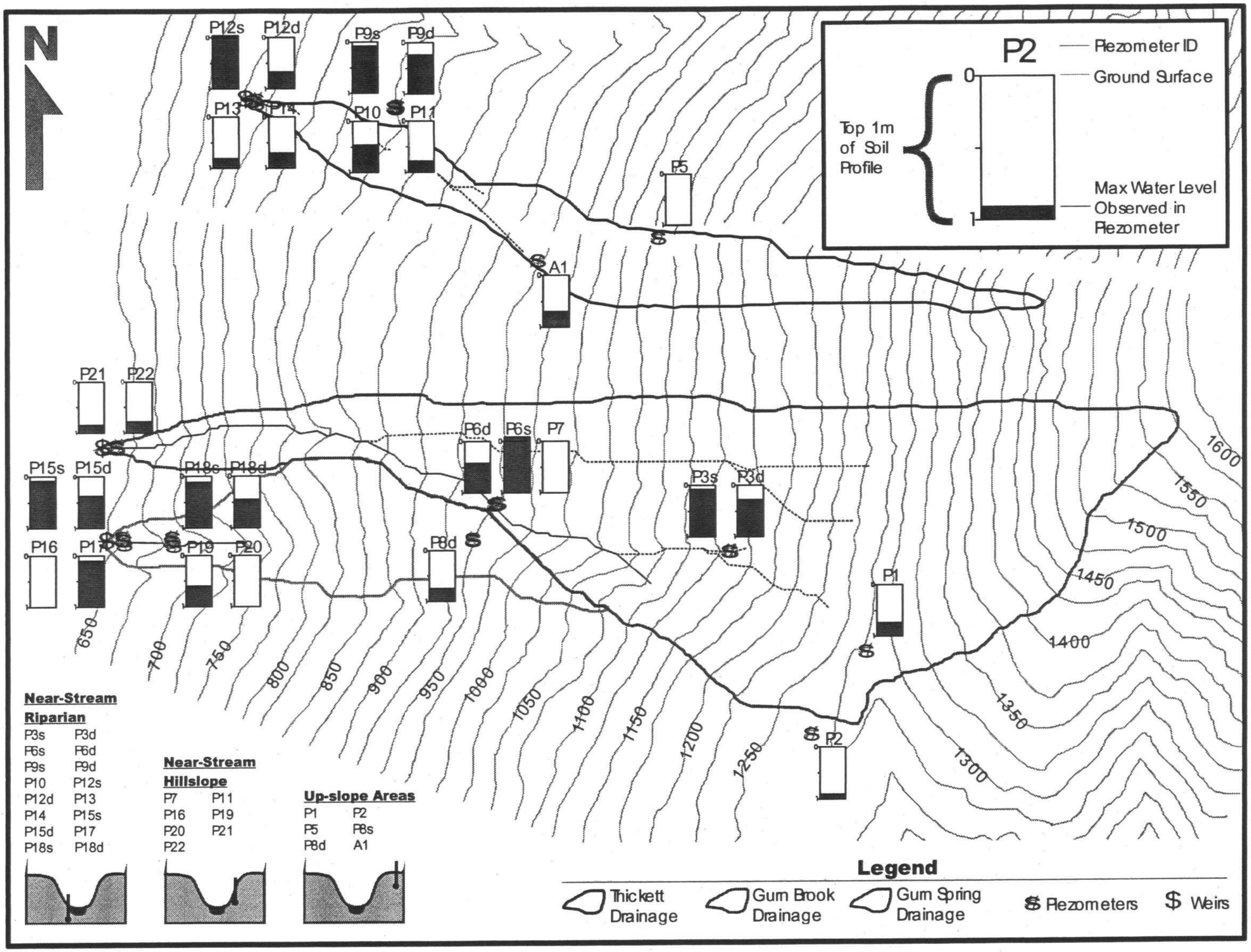

Figure 3.8. Distribution of maximum water levels recorded in piezometers on Ringrose Slope, winter/spring 2002. The inset in the bottom left-hand corner provides information regarding the hydrogeomorphic position for each piezometer.

3.3.2 Distribution of maximum recorded water levels

Piezometers located in near-stream riparian (NSRIP) areas (e.g. P3d, P15d) experienced relatively high water levels (Figure 3.8). With the exception of P12s, a shallow piezometer located within the TH stream channel during high flows, water levels in piezometers located in NSRIP areas immediately upslope of the weir on Thickett Creek were lower than those in NSRIP areas in the Gurn Spring and Gurn Brook catchments. Shallow piezometers located in NSRIP areas experienced higher water levels than deeper piezometers located in the same areas. Piezometers located in near-stream hillslope areas (NSHIL) (e.g. P7, P21) and those located in upslope contributing areas (UP) (e.g. P2, P5) exhibited relatively low water levels (Figure 3.9).

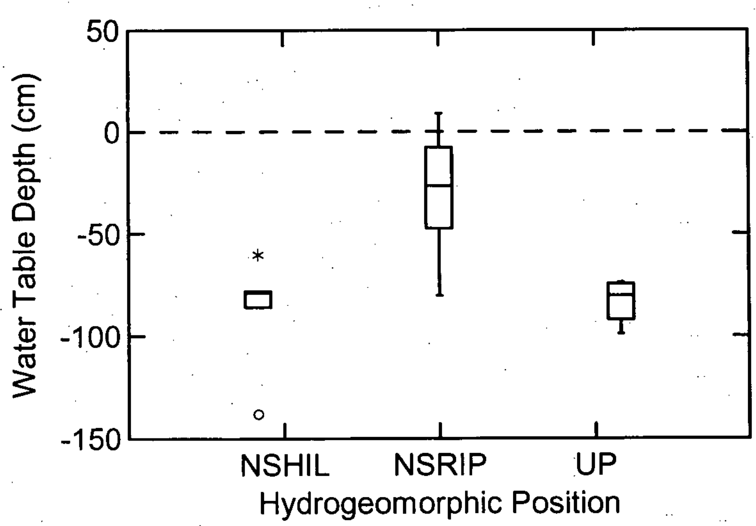

Figure 3.9. Box plot showing maximum water levels in piezometers grouped by hydrogeomorphic position: near-stream riparian areas (NSRIP), near-stream hillslope areas (NSHIL), and upslope contributing areas (UP). Water levels are expressed relative to the ground surface (0).

3.4 OBSERVATIONS OF SURFACE FLOW

This section presents observations of overland flow made on Ringrose Slope during the field season. Section 3.4.1 presents observed saturation overland flow and section 3.4.2 presents observed surface flow along roads.

3.4.1 Saturation overland flow (SOF)

The timing and location of saturation overland flow (SOF) were recorded throughout the field season on an opportunistic basis. Approximate locations of SOF observed between Feb 11, 2002, and May 16, 2002, are presented in Figure 3.10 and cross-referenced with brief descriptions in Table 3.4. Detailed descriptions of observed SOF are presented in Appendix C. It should be noted that the maps consider observed SOF only, and may not include all locations experiencing active SOF for a given time period. Due to the relatively large area of the field site, its steep terrain, and the fact that access was by foot only, it was impossible to make regular visits to all areas of the field site.

Despite these qualifications, observations indicated that locations of SOF did not exhibit a high degree of connectivity in Thickett Creek (Figure 3.10). In Gurn Spring and Gurn Brook, observed surface flow was mainly restricted to the stream channel itself, or to small zones immediately next to the stream channel. These observations are consistent with maximum water levels measured in piezometers (Figure 3.8).

Table 3.4. Observations of saturation overland flow (for cross-reference with Figure 3.10 and Appendix C).

Map Label	Date of First Observation	Date of Last Observation	Comments
1	Feb 25, 2002	Apr 24, 2002	Seepage generating downslope overland flow.
2	Mar 31, 2002	Apr 24, 2002	Incipient channel feature and diffuse surface saturation.
3	Apr 9, 2002	Apr 18, 2002	2 parallel incipient channel features.
4	Apr 10, 2002	Apr 18, 2002	Incipient micro-channel at base of convergent slopes.
5	Apr 10, 2002	Apr 18, 2002	Seepage and surface saturation.
6	Apr 15, 2002	Apr 15, 2002	Incipient channel feature intersecting road.
7	Apr 15, 2002	Apr 18, 2002	Surface saturation.
8	Apr 15, 2002	May 16, 2002	Multiple seeps generating downslope overland flow.
9	Apr 16, 2002	Apr 16, 2002	Incipient micro-channel at base of convergent slopes.
10	Apr 16, 2002	Apr 24, 2002	Seepage.
11	Apr 16, 2002	Apr 16, 2002	Upslope extension of #3.
12	Apr 16, 2002	Apr 24, 2002	Downslope convergence of channel features in #3.
13	Apr 17, 2002	Apr 24, 2002	Seepage generating downslope overland flow.
14	Apr 18, 2002	Apr 24, 2002	Incipient channel feature intersecting road.
15	Apr 18, 2002	May 16, 2002	Seepage generating downslope overland flow.
16	May 15, 2002	May 15, 2002	Incipient channel feature intersecting road.

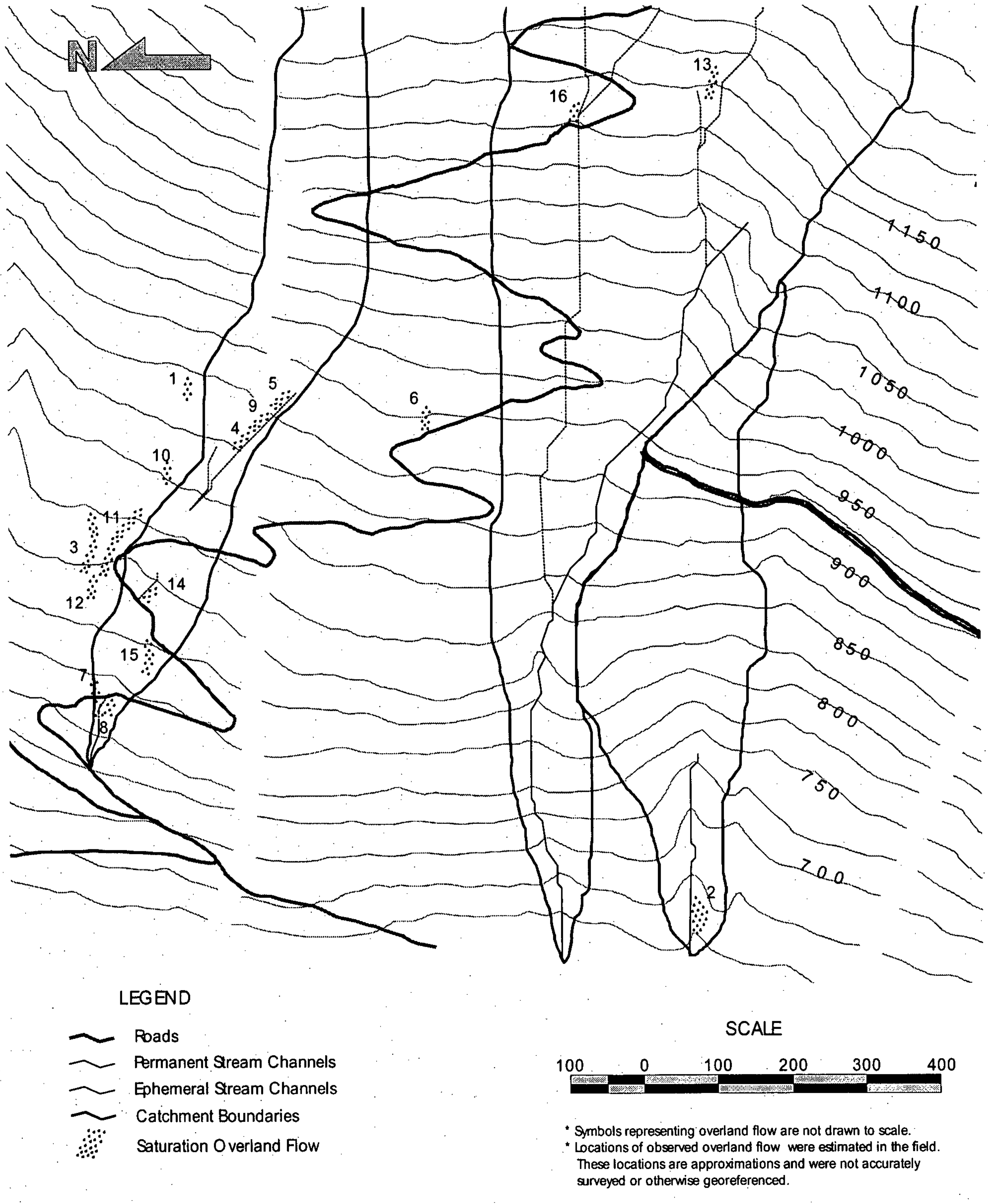

Figure 3.10. Saturation overland flow observed between Feb 11, 2002 and May 16, 2002. Numbers are provided for cross-reference with Table 3.4 and Appendix C. No observations were made above 1275 m, and no SOF was observed above 1200 m (the upslope extent of the above map).

3.4.2 *Overland flow along roads*

Figures 3.11 to 3.13 show overland flow observed along roads during the periods Apr 15-18, 2002, Apr 22-24, 2002, and May 15-16, 2002, respectively. Note that arrows representing overland flow indicate the direction of flow, but are not intended to indicate relative volumes of flow. Locations of observed overland flow along roads were estimated in the same manner as for saturation overland flow. Some locations were surveyed using differential GPS.

Overland flow along roads was greatest during the period Apr 15-18, 2002 (Figure 3.11). Flows were only observed below 1000 m, the approximate elevation of the snow line (Figure 3.3), and were higher at all recorded locations than on subsequent visits. The connectivity of surface flows along roads was highest during this period, with some sections of the road carrying water through multiple switchbacks or long distances along straight sections. The estimated proportion of water diverted off the road surface at many points of diversion (PODs) was lower during this period. This resulted from higher rates of spillage out of PODs and back onto roads, as many PODs were incapable of handling the higher volumes of flow. Subsurface flow interception along cut-banks was also at its highest during this period, with water often observed dripping or flowing freely from the soil profile.

During the following week, overland flow along roads persisted in many locations, but the magnitude and continuity of flows was diminished (Figure 3.12). Between Apr 22, 2002, and Apr 24, 2002, all overland flow along roads was observed below the snow line (1175 m), with the snowline often following the road within the Gurn Brook catchment. One new occurrence of overland flow was observed just below 1175 m. This followed the road for a short distance before being diverted off the road by a wooden cross-ditch. Active PODs generally diverted the majority of overland flow off roads during this period, with proportions estimated to be > 90% for 11 of 12 active PODs. Relative to the week prior, overland flow along roads tended to be more intermittent during this period with flows appearing and then disappearing into the roadbed along some sections.

Although the snow cover had left the catchments entirely by May 15-16, significant overland flow persisted along the road just below 1175 m and above and below the lower climate station between 900 and 1000 m (Figure 3.13). Flows persisted in some locations at lower elevations within the Thickett Creek catchment, but these were limited to slow trickles. During this period 12 of the 13 active PODs were estimated to be diverting > 98% of flows off road surfaces.

Overland flow along road surfaces was observed crossing the TH and GB catchment boundaries during each of the three observation periods. There appears to be zero potential for cross-catchment flow of water along roads in GS, and minimal potential in GB. Because of the high road density at lower elevations near the TH catchment outlet, the potential for cross-catchment flow along roads in TH appears to be relatively high. This is particularly true during the period April 15-18, 2002, when flow volumes were highest and POD's were least effective at removing water from road surfaces.

APRIL 15-18, 2002

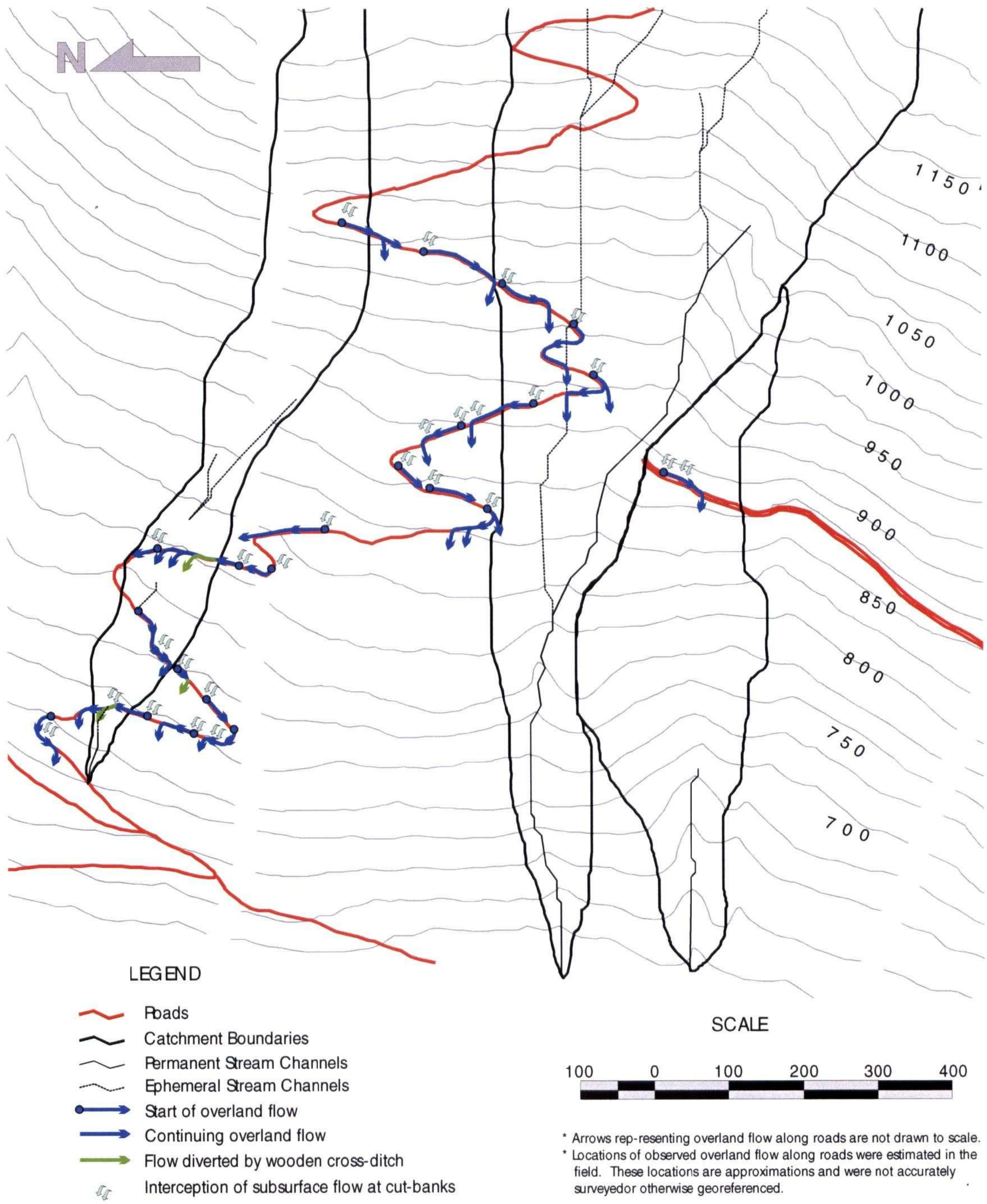

Figure 3.11. Overland flow observed along road surfaces between April 15, 2002 and Apr 18, 2002. Discontinuous arrows (i.e. arrows that are not connected) indicated intermittent flow while connected arrows indicate connectivity of overland flow along the road. Arrows with black-ringed dots on the end represent the start of flow along roads, and were generally associated with interception of subsurface flow at cut-banks on the upslope side of roads. Arrows leaving the road surface and pointing downslope indicate points where flow was diverted off the road surface. No observations were made above 1275 m, and no overland flow was observed above 1200 m (the upslope extent of the above map).

APRIL 22-24, 2002

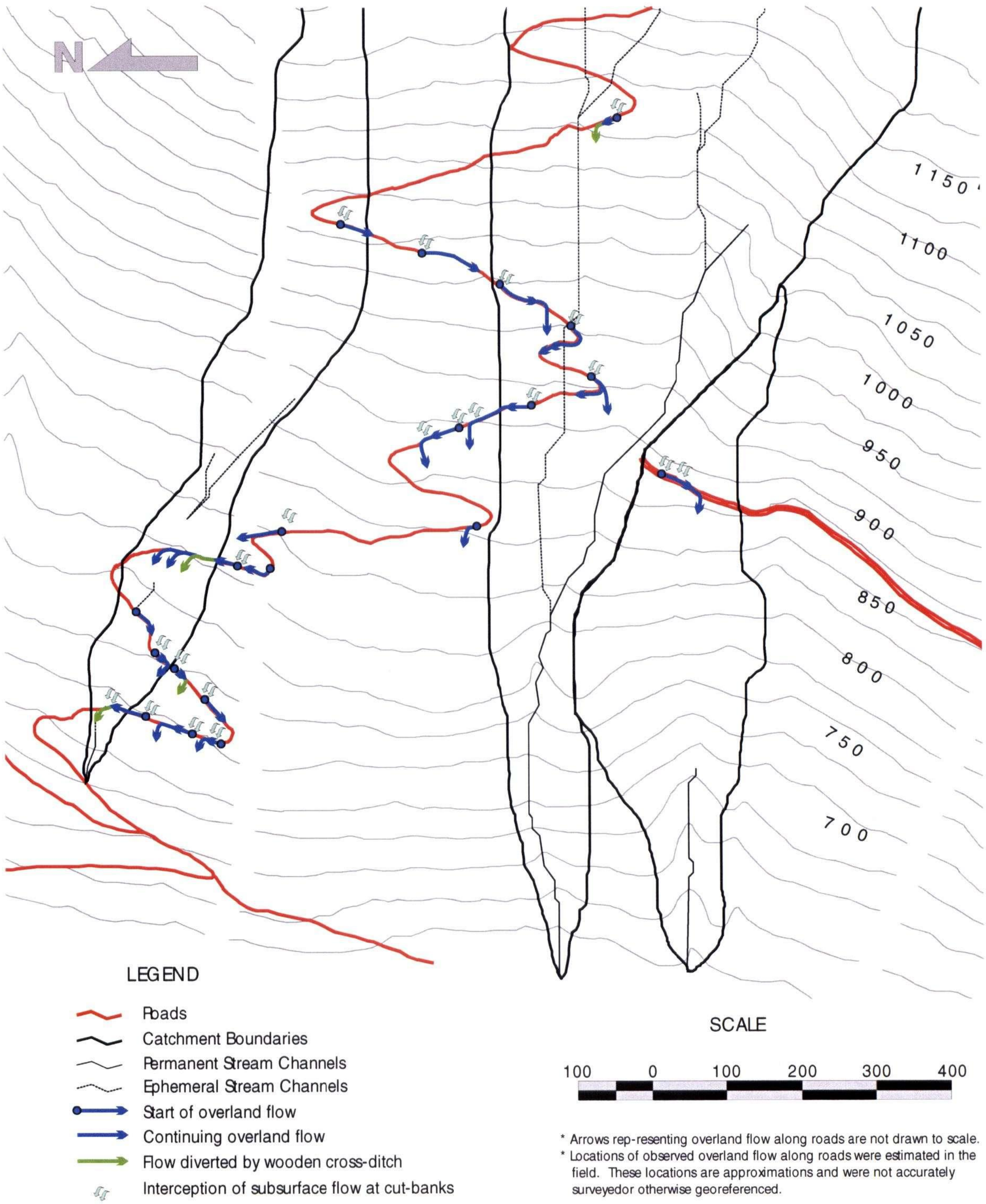

Figure 3.12. Overland flow observed along road surfaces between April 22, 2002 and April 24, 2002. See caption for Figure 3.11 for further information. No observations were made above 1275 m, however no overland flow was observed above 1200 m (the upslope extent of the above map).

MAY 15-16, 2002

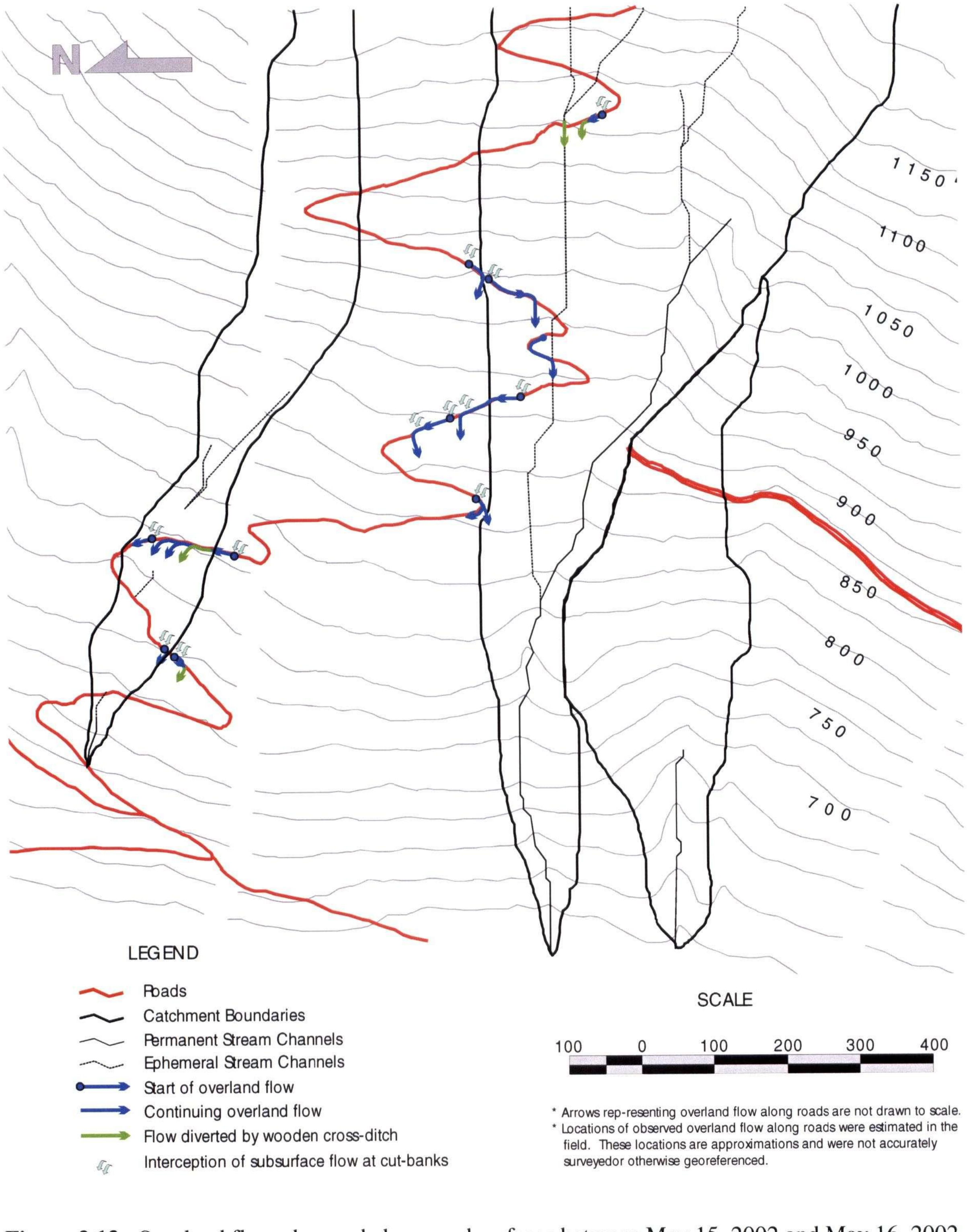

Figure 3.13. Overland flow observed along road surfaces between May 15, 2002 and May 16, 2002. See caption for Figure 3.11 for further information. No observations were made above approximately 1275 m, however no overland flow was observed above 1200 m (the upslope extent of the above map).

3.5 ISOTOPIC CONCENTRATIONS

3.5.1 *Isotopic concentrations in melt and rainwater*

In this section, the term "integrated melt" will be used to refer to a sample composed of melt and rainwater, and "melt sampler" will refer to the sampling trays used to collect either integrated melt or rainwater. Isotopic concentrations of melt and rainwater samples collected from melt samplers are presented Appendix D. This section presents results of analysis of isotopic concentrations in integrated melt and rain samples and explores their variation through time and space.

Results are presented for samples collected on four dates: March 24, 2002, and March 27, 2002, were days of rain-on-snow above 1175 m, while April 10, 2002 followed a 5-day dry period and experienced minor rainfall (< 5 mm). Finally, a number of rainfall samples along with integrated melt samples were collected on April 14, 2002.

Spearman rank order correlation analysis revealed statistically significant relations between $\delta^{18}O$ and elevation ($p \leq 0.05$) for samples collected on each date save March 24, 2002 (Table 3.5, Figure 3.14). Rainwater samples were generally less depleted in ^{18}O relative to integrated melt samples. Though not statistically significant, samples collected Mar 24, 2002, suggested a positive relation between $\delta^{18}O$ and elevation. Negative relations were seen for all other time periods (Figure 3.14). Statistically significant correlations were found between $\delta^{18}O$ and time for integrated melt samples collected from most elevations/samplers (Table 3.6), with water inputs becoming increasingly enriched in oxygen-18 over time (Figure 3.15).

Table 3.5. Results of Spearman correlation analysis comparing variation in isotopic concentrations of integrated melt and rainwater samples with changes in elevation. Data are stratified by date to control for temporal variability in isotopic concentrations of water samples.

Date(s)	Sample Type	n	r_s	p
Mar 24, 2002	Integrated Melt	6	0.714	> 0.05
Mar 27, 2002	Integrated Melt	6	-0.943	0.05
Apr 10, 2002	Integrated Melt	7	-0.786	0.025
Apr 14, 2002	Rainwater	5	-0.9	0.05

Table 3.6. Results of Spearman correlation analysis comparing variation in isotopic concentrations of integrated melt samples over time. Data are stratified by elevation to control for spatial variability in isotopic concentrations of water samples.

Elevation (m)	Sample Type	n	r_s	p
1275	Integrated Melt	5	0.5	> 0.05
1270	Integrated Melt	9	0.561	> 0.05
1135	Integrated Melt	10	0.952	< 0.005
1060	Integrated Melt	6	1.000	< 0.01
945	Integrated Melt	6	0.886	< 0.025
935	Integrated Melt	7	0.786	0.025
825	Integrated Melt	6	0.943	< 0.01
655	Integrated Melt	4	0.4	> 0.05

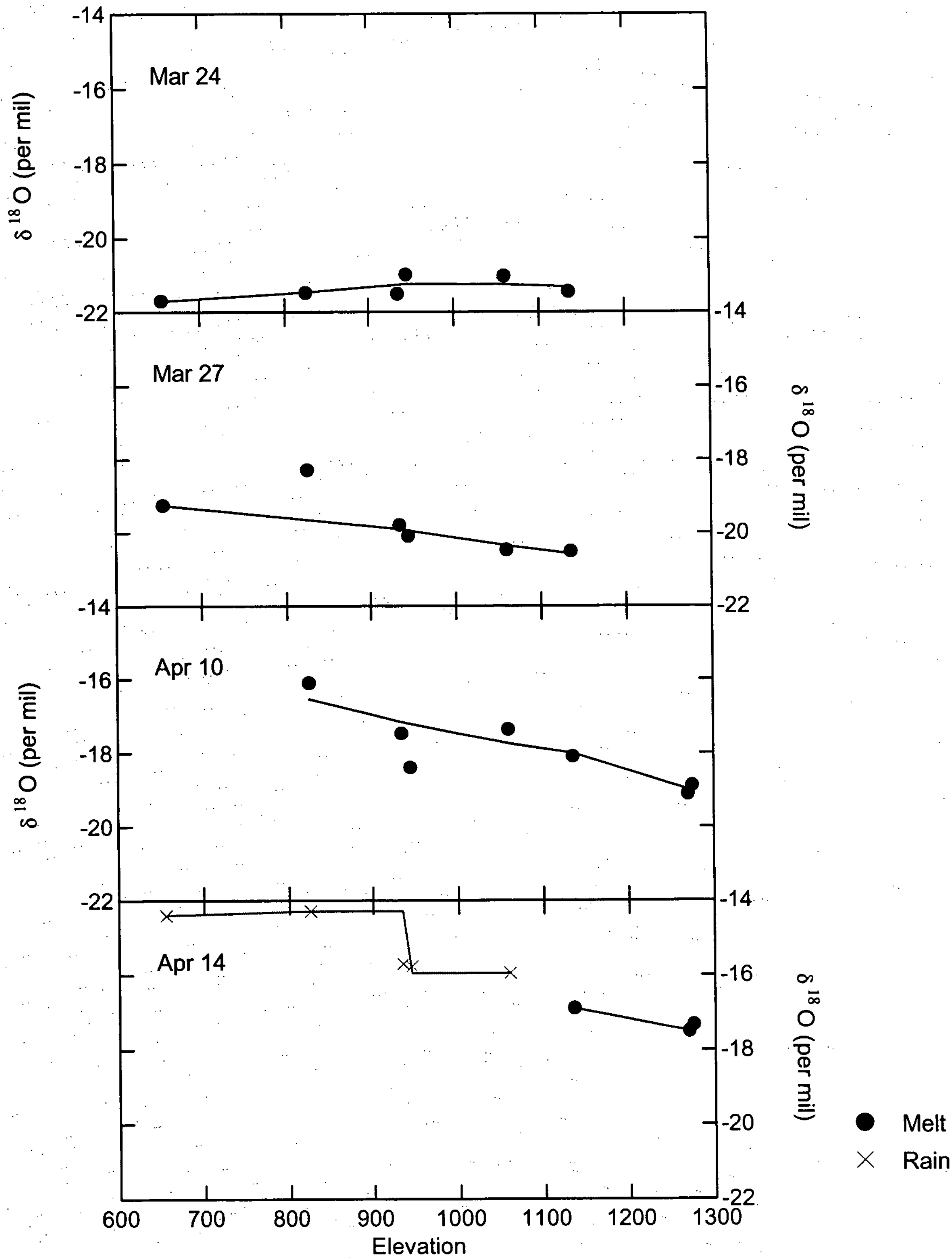

Figure 3.14. Variation in isotopic concentrations of meltwater and rainwater with changes in elevation. Data for three periods of melt (top 3) and one period of rain at lower elevations (bottom) are presented (LOWESS smoother, tension = 0.9).

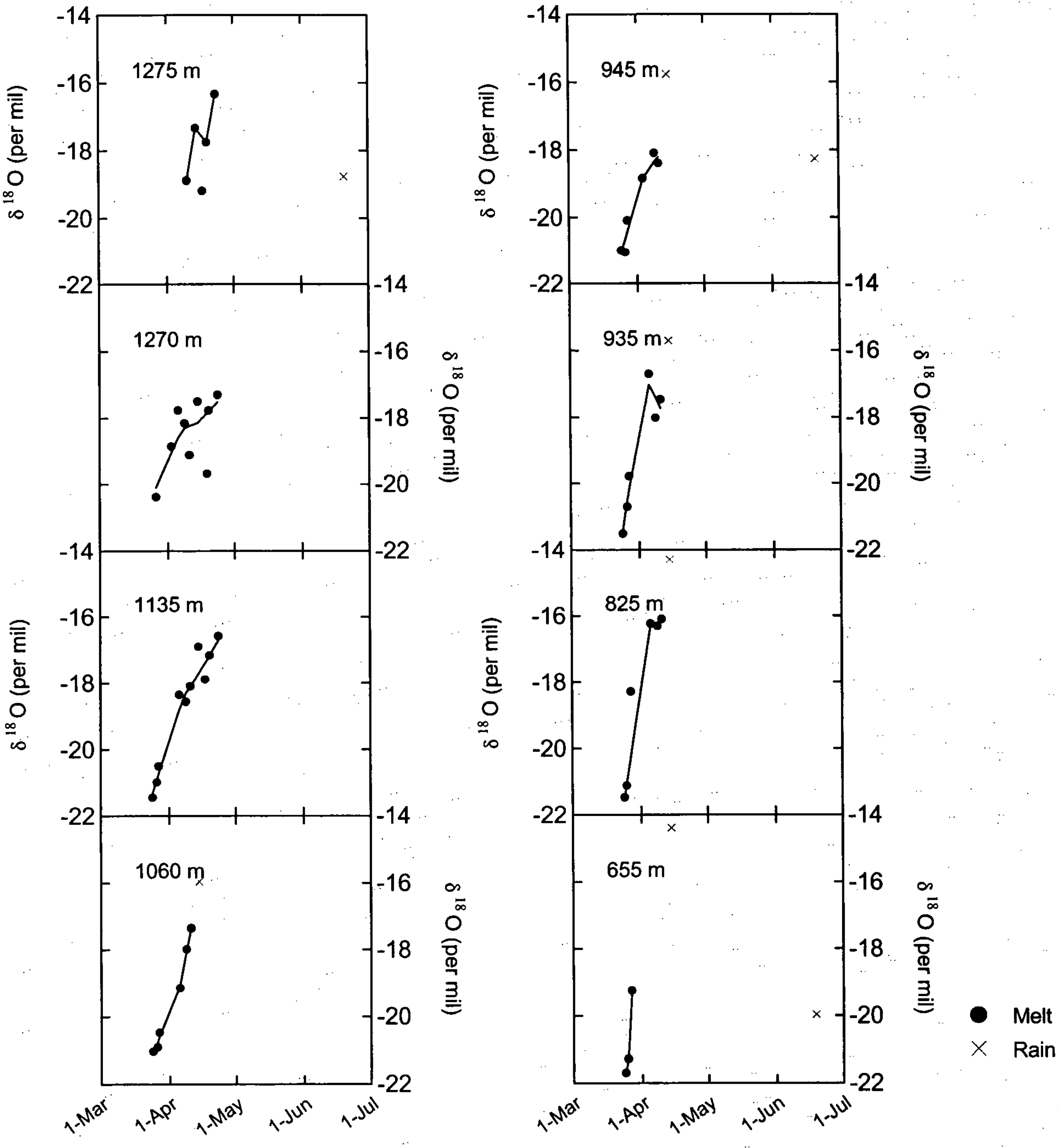

Figure 3.15. Time series of isotopic concentrations in meltwater measured at four elevations. Rainwater samples are included for comparison; however, the LOWESS smoother (tension = 0.9) is fitted to the meltwater data points only.

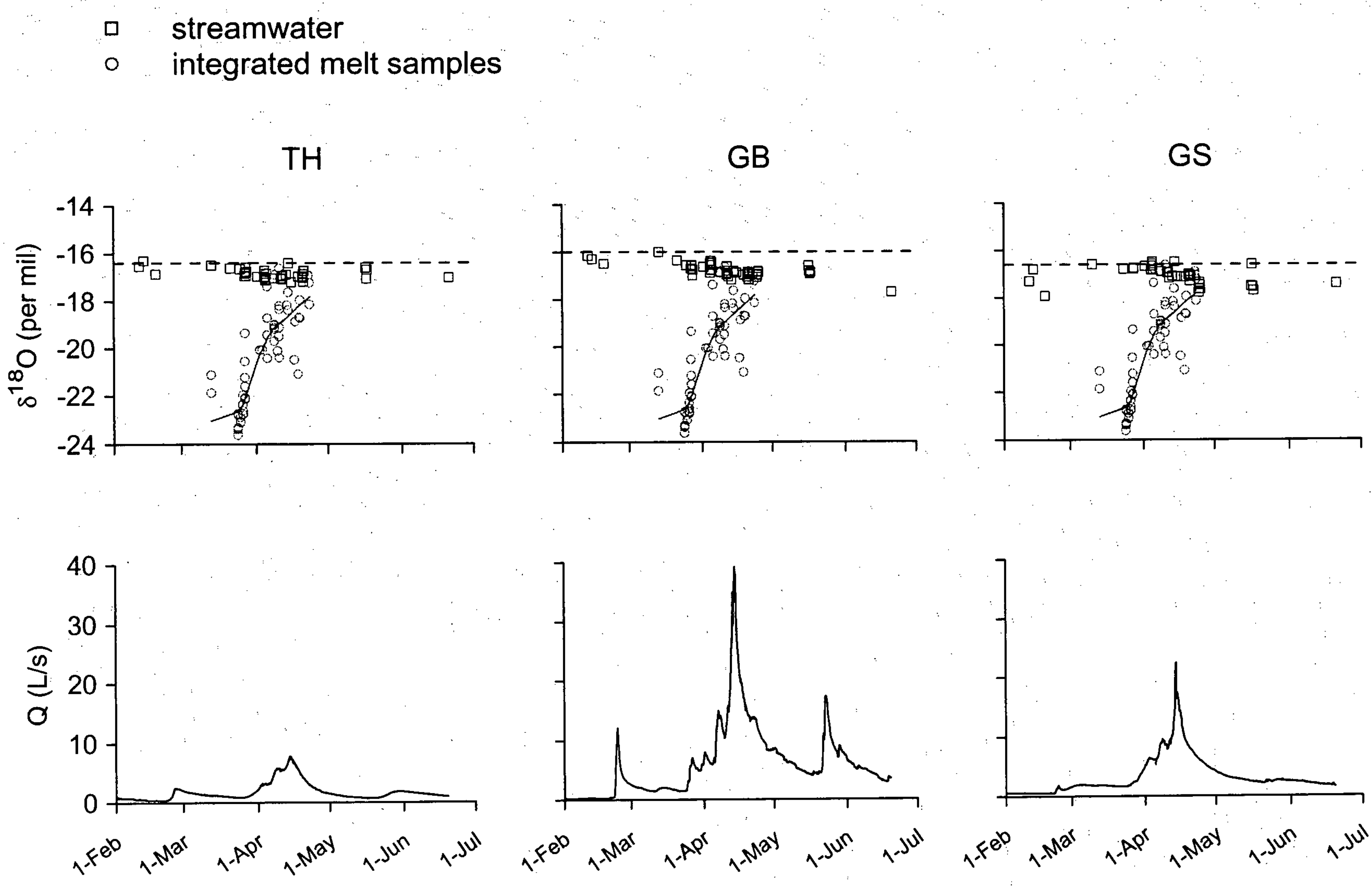

Figure 3.16. Time series of isotopic concentrations in streamwater and meltwater compared to streamflow. Dashed lines indicate baseflow concentrations.

3.5.2 Isotopic concentrations in streamwater

Oxygen-18 concentrations were similar amongst streamwater samples collected Dec. 20, 2001 (-16.5 for TH, -16 for GB, -16.9 for GS) and Feb. 11-13, 2002 (-16.53 for TH, -16.15 for GB, -17.3 and -16.8 for GS) indicating little isotopic variation in during baseflow. The concentration of oxygen-18 tended to decrease in all streams up until about the time of peak flows (Figure 3.19), becoming similar to that of integrated melt samples collected at that time (Figure 3.16). Streams displayed differing concentrations early in the season, with concentrations becoming similar around the time of peak flows. Following peak flows, streams again displayed differing concentrations. Concentrations were lowest in Gurn Spring both prior to and following peak flows. Both early in the season and after peak flows, Thickett Creek and Gurn Brook streamwaters were more enriched in oxygen-18 relative to Gurn Spring (with one exception being the water sampled from GB on June 18, 2002).

3.5.3 Isotopic concentrations in subsurface water

Subsurface water sampled from piezometers in the TH and GS catchments contained similar concentrations of oxygen-18 (Figure 3.17). Excepting the single sample collected February 11, 2002, samples collected from GB piezometers were depleted in $\delta^{18}O$ relative to samples collected from TH and GS. In TH and GS piezometers there was little variation in $\delta^{18}O$ among the three sampling dates. In GB piezometers, $\delta^{18}O$ decreased throughout the freshet period. Concentrations of oxygen-18 in all piezometer samples collected during base-flow conditions (Februaru 11, 2002) were similar.

3.6 WATER CHEMISTRY

This section presents result from analyses of water chemistry. Section 3.6.1 provides a discussion of water chemistry in subsurface waters sampled from piezometers, while section 3.6.2 examines streamwater chemistry. Concentration – discharge relations are presented in section 3.6.3. Section 3.6.4 presents results from principal components analyses of water chemistry from each of the three streams and from the whole of Ringrose Slope.

3.6.1 Water chemistry in piezometers

Water samples were collected from the majority of active piezometers on each of three dates (Feb 11, 2002, May 16, 2002, and Jun 18, 2002), except where water levels on one or more of these dates were insufficient for sample collection (e.g., P20) or piezometers failed to refill within a short time after being pumped dry (e.g., P12s). Only those piezometers located in near-stream riparian areas (NSRIP) contained enough water on all three sampling dates for sample collection. Exceptions were P11, a near-stream hillslope (NSHIL) piezometer located just north of the TH catchment from which samples were collected on all sampling dates, and P20, a NSHIL piezometer located in the GS catchment that produced a sample on Jun 18, 2002. Both P11 and P20 were located on short (1-2 m), moderately angled slopes defining the adjoining riparian valley bottoms. No piezometers located in upslope contributing areas (UP) contained enough water on any of the sampling dates to produce a water sample.

Concentrations of Ca, Mg, Si, EC, and Na concentrations appeared higher in water collected from GS piezometers (Figure 3.17). Water from GB piezometers contained the lowest concentrations of K, and the ratio (Na+K)/(Na+K+Ca+Mg) (R_{NA-K}). Within catchments, chemical concentrations vary amongst piezometers. Concentrations of most chemical parameters varied throughout the freshet period. Concentrations of all parameters appear to decrease with increasing elevation (Figure 3.18). However, concentrations varied substantially amongst piezometers at the same elevation. Spearman correlation analysis revealed significant inverse relations between elevation and concentrations of Ca, Mg, Si, and EC in piezometer samples collected February 11, 2002 ($p <= 0.05$, $n = 8$) (Table 3.7).

A comparison of $R_{NA/K}$ values in piezometer samples and in streamwater samples revealed the following (Figure 3.19):

1. Higher values of the ratio were measured in streamwater than in subsurface waters at GB.
2. Values of the ratio in TH and GS streamwater appear to fall within the range of values measured in subsurface waters.
3. The ranges of the ratio in subsurface water and streamwater TH are almost identical.
4. The subsurface water chemistry in the GS catchment is more variable than GS streamwater chemistry.

Table 3.7. Spearman correlation analysis showing relation between elevation and concentrations of chemical parameters in piezometer samples collected February 11, 2002.

Chemical Parameter	n	r_s	P
Ca	8	-0.908	< 0.005
K	8	-0.282	> 0.05
Mg	8	-0.786	< 0.025
Na	8	-0.503	> 0.05
Si	8	-0.921	< 0.005
$\delta^{18}O$	8	-0.216	> 0.05
R_{NA-K}	8	0.061	> 0.05
EC	8	-0.651	< 0.05

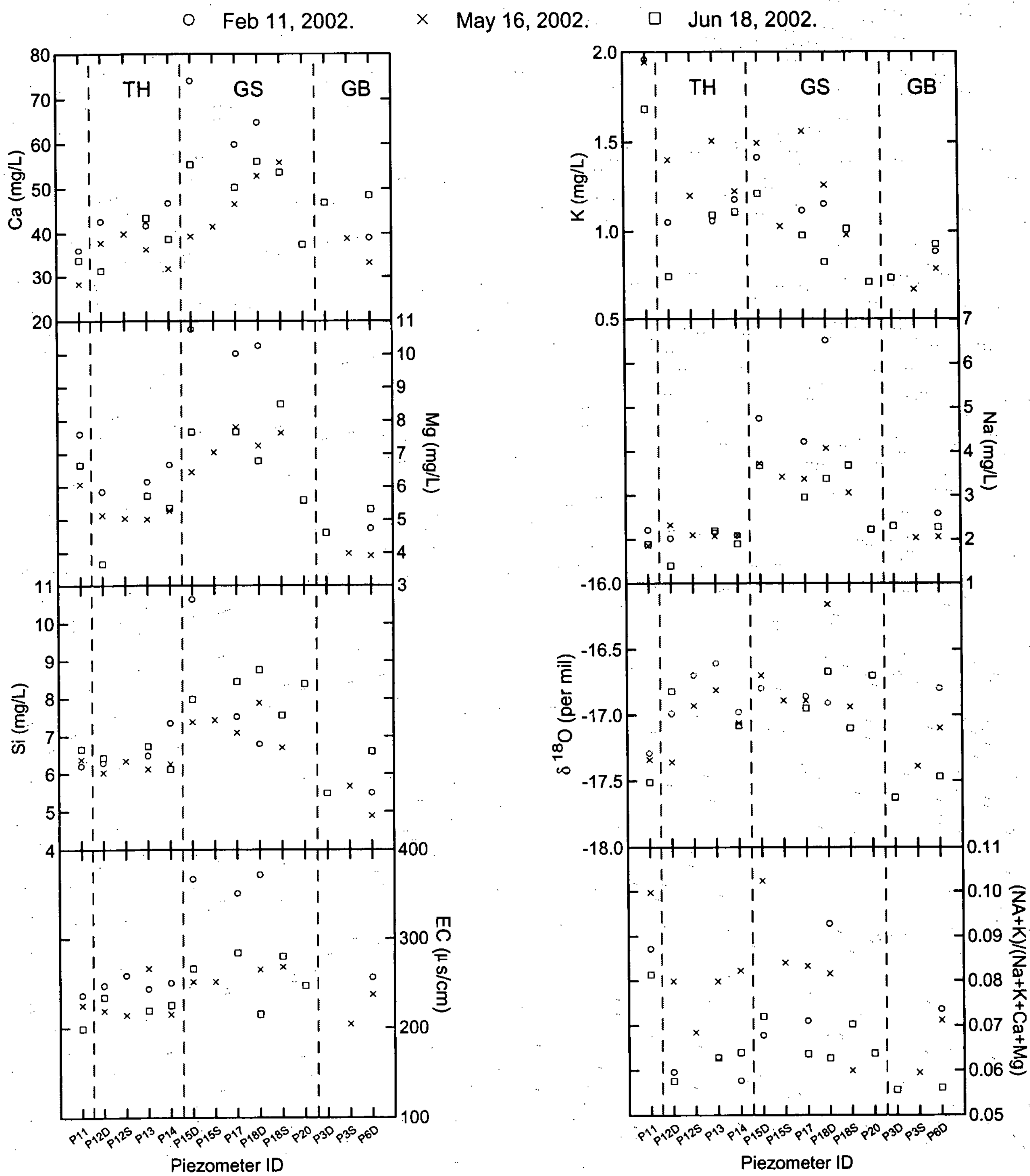

Figure 3.17. Concentrations of eight chemical parameters in subsurface water collected from active piezometers on three sampling dates. Dashed vertical lines separate piezometers from the TH, GS, and GB catchments. P11 lies on Ringrose Slope just north of the Thickett Creek catchment.

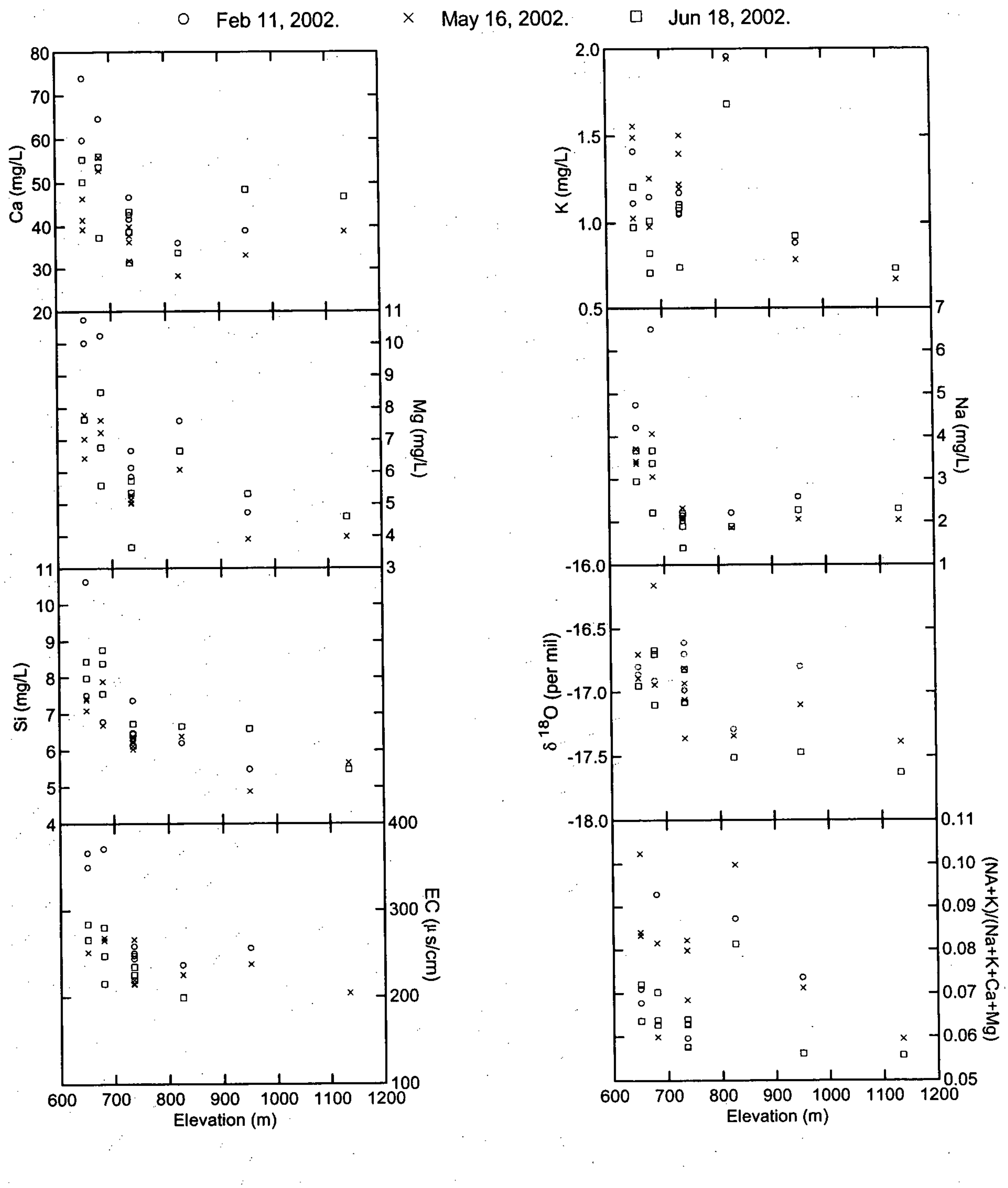

Figure 3.18. Concentrations of chemical parameters in subsurface waters plotted against elevation. Samples were collected from active piezometers on three seperate dates. Elevations of piezometers were either estimated using an altimeter and reference to topographic features or surveyed using differential GPS.

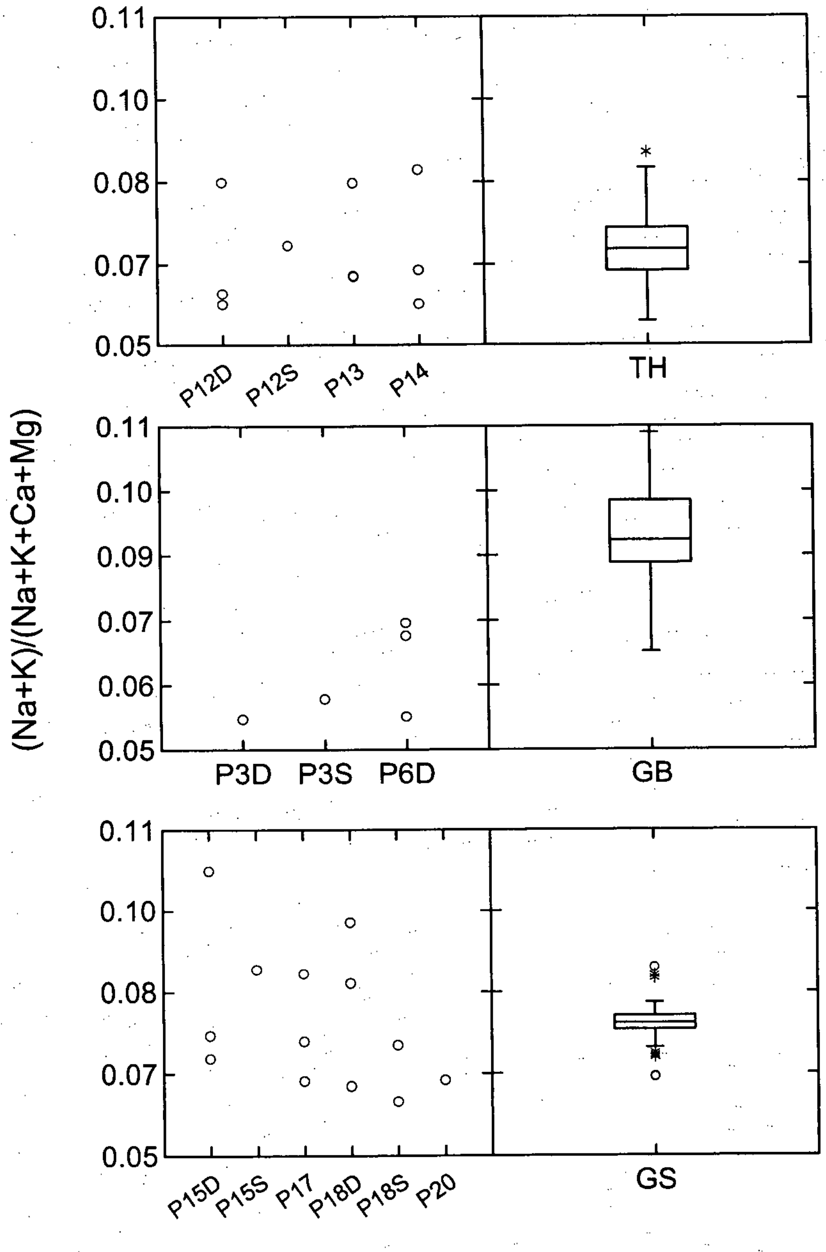

Figure 3.19. Comparison of $R_{NA/K}$ values measured in subsurface water sampled from piezometers located in the TH, GB, and GS catchments (scatterplots at left) with that measured in streamwater collected from TH, GB, and GS (box plots at right).

3.6.2 *Water chemistry in streamflow*

Concentrations of the four major cations (Ca, K, Na, Mg) were lowest in GB at all times throughout the freshet (Figure 3.20). Cation concentrations were highest in GS streamwater except during peak flows, when they dropped to similar concentrations as in TH streamwater. The concentrations of Ca, Mg, sum of cations (Ca + Mg + Na + K), and electrical conductivity (EC) exhibited similar variation through time, dominated by a decrease associated with peak streamflow, followed by an increasing trend through the post-peak discharge recession. Spearman correlation analysis revealed that EC provides a good proxy for total cation concentrations in streamwater ($r_s = 0.954$, $P = 0.005$, $n = 130$).

Silica (Si) concentrations were highly variable, with no discernable pattern emerging over the freshet period. Concentrations were generally similar in TH and GB streamwater, and highest in GS streamwaters. Dissolved organic carbon (DOC) and $R_{NA\text{-}K}$ were highest in GB and lowest in TH streamwater. DOC and the ratio displayed an overall increase up to the time of peak flows for all streams.

3.6.3 *Concentration – discharge relations*

For Thickett Creek, the relations between Ca and EC vs. discharge exhibited clockwise hysteresis. During the falling limb, Ca and EC followed a curvilinear trend with concentrations increasing rapidly as flows decreased towards original levels (Figure 3.21). Concentrations of Mg were also higher during the rising limb; however, the hysteresis observed for Ca and EC was less marked. Concentrations of all cations were more variable at a given discharge during rising stage. $R_{NA\text{-}K}$ increased gradually with increasing discharge, with the ratio being higher during falling stage. $\delta^{18}O$ decreased with increasing discharge, and showed no obvious difference between samples collected during rising and falling stages. Silica concentrations varied chaotically with discharge, with no apparent difference between samples collected during rising and falling stages.

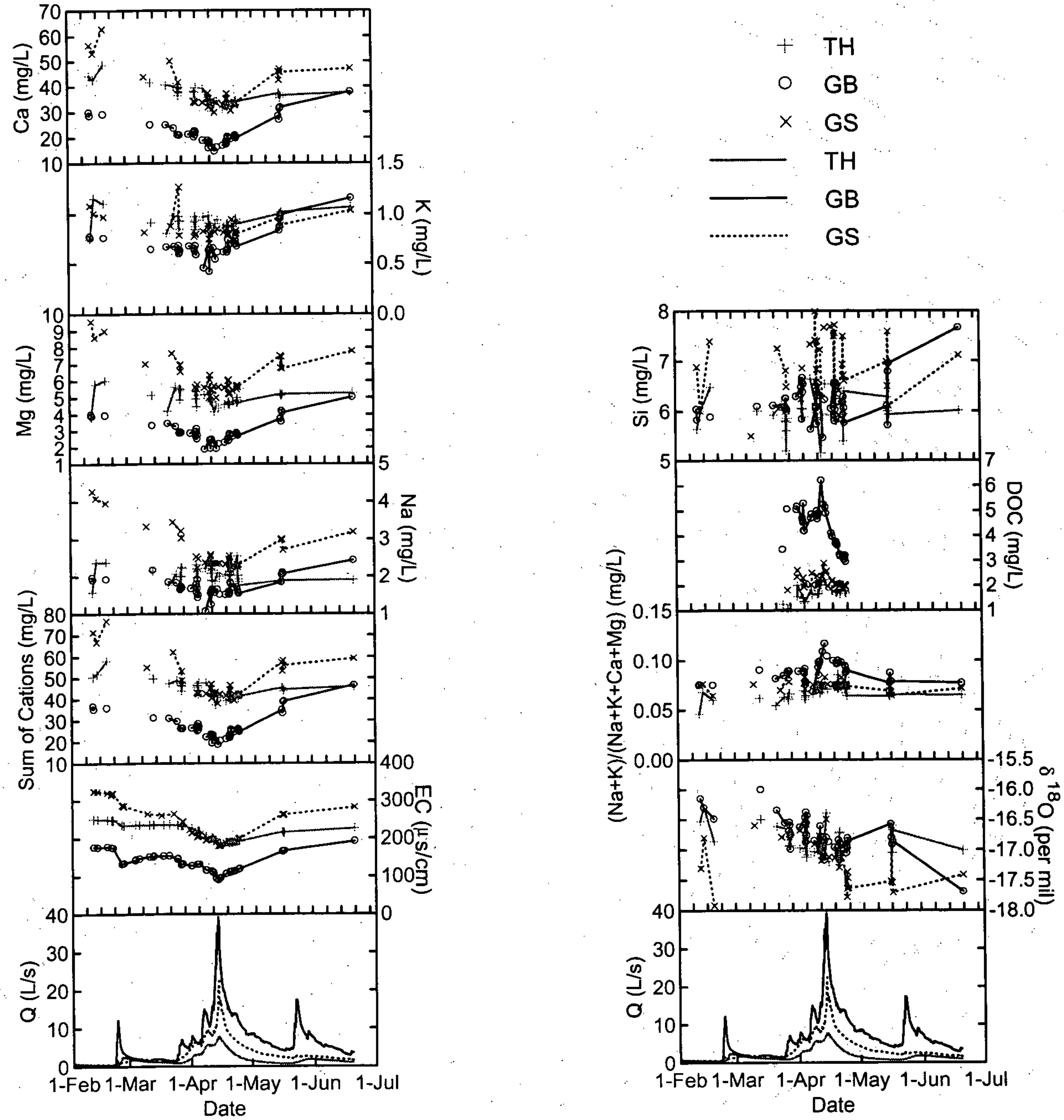

Figure 3.20. Time series of chemical parameters measured in streamwater at the weirs on the three study streams. Hydrographs are included for reference at the bottom.

For Gurn Brook, similar relations are observed for Ca, Mg, and EC (and to a lesser degree K): concentrations begin relatively high during rising stage at low flows, then drop steadily with increasing discharge (Figure 3.22). During falling stage, points generally plot along the same line as during rising stage; however, there is a rapid increase in concentrations below 5 L/s, resulting in higher late-season concentrations of Ca, Mg, and EC than during pre-melt base flow conditions. $R_{NA\text{-}K}$ increased rapidly with increasing discharge, following a roughly linear trend. No obvious distinction was observed between samples collected during the rise and fall in the hydrograph. $\delta^{18}O$ decreased with increasing discharge, with samples collected during falling stage generally plotting below those collected during rising stage for a given discharge. Silica concentrations show a decrease with increasing discharge; however, the relation is weak and no distinction between samples collected during rising and falling stage is seen. Concentrations of all chemical parameters were similarly variable under conditions of rising and falling stage.

The concentration – discharge relations for Gurn Spring (Figure 3.23) display a number of important differences from those of GB and TH:

1. Concentrations of cations and EC do not exhibit hysteresis.
2. No clear concentration-discharge relation was observed for $R_{NA\text{-}K}$.
3. $\delta^{18}O$ generally increased with increased discharge during rising stage, but varied oppositely during falling stage.
4. Silica varied relatively chaotically with discharge.

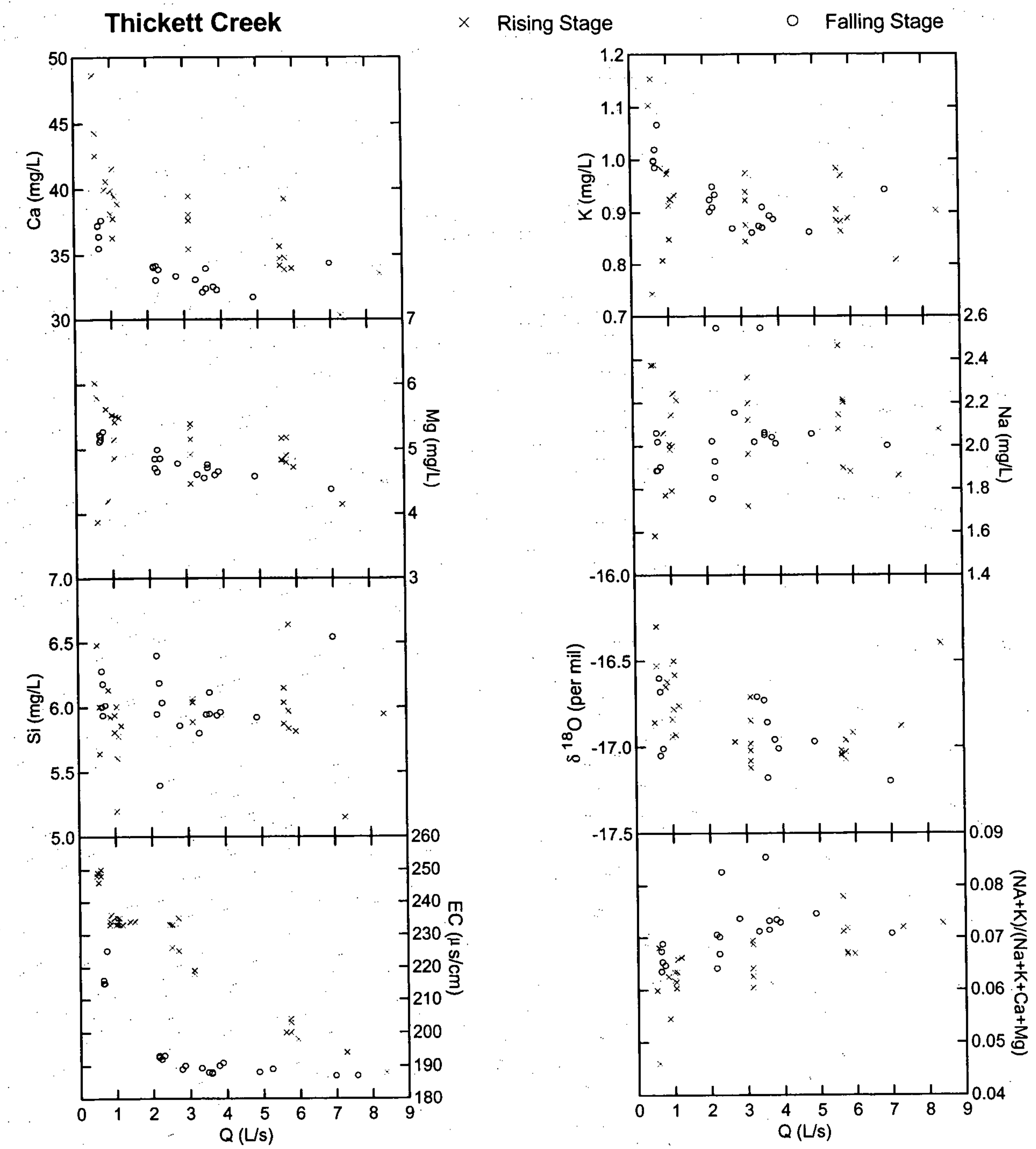

Figure 3.21. Concentration-discharge relations for Thickett Creek. Samples collected on the rising and falling limbs of the hydrograph are represented by the black circles and grey crosses, respectively.

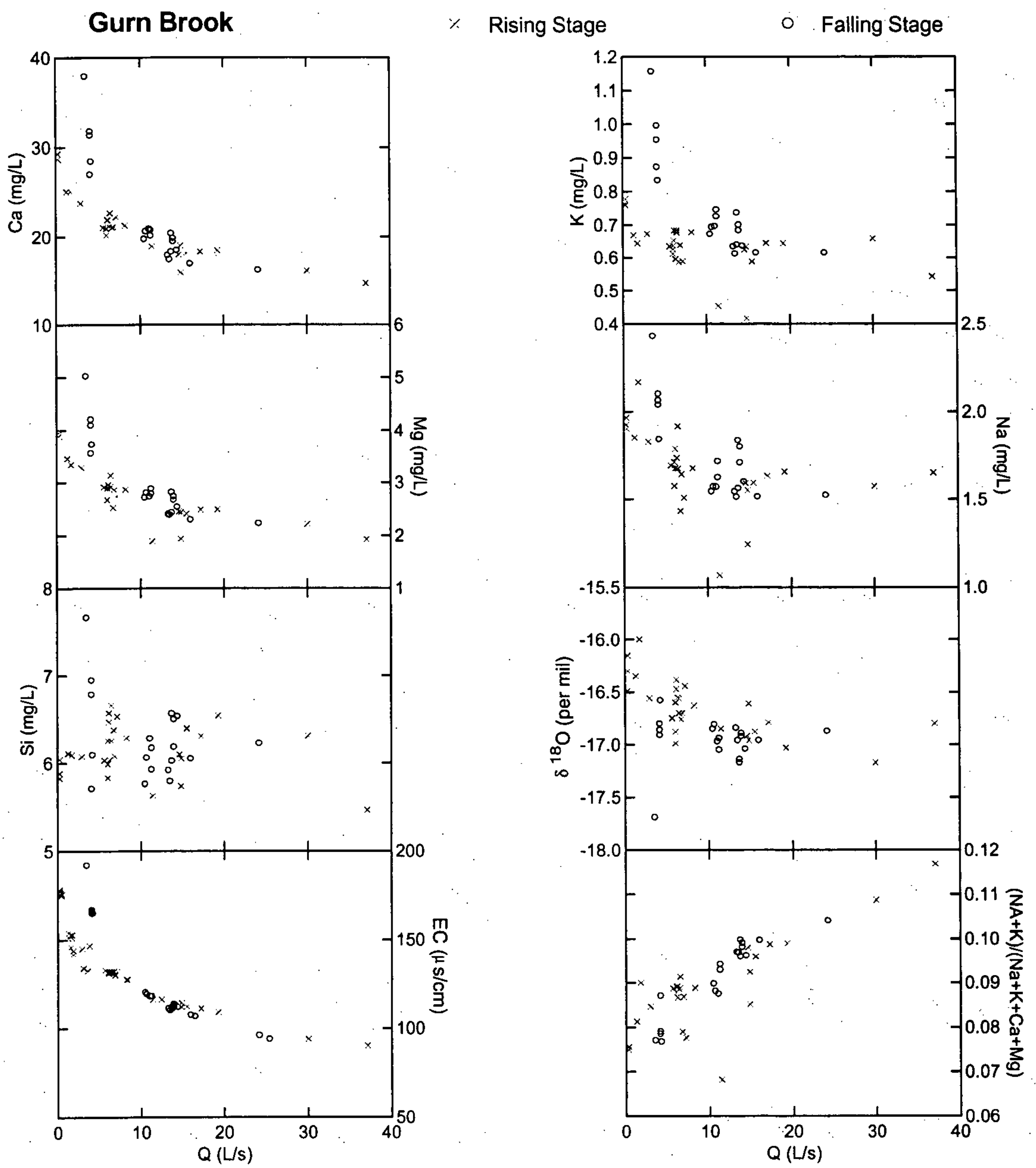

Figure 3.22. Concentration-discharge relations for Gurn Brook. Samples collected on the rising and falling limbs of the hydrograph are represented by the black circles and grey crosses, respectively.

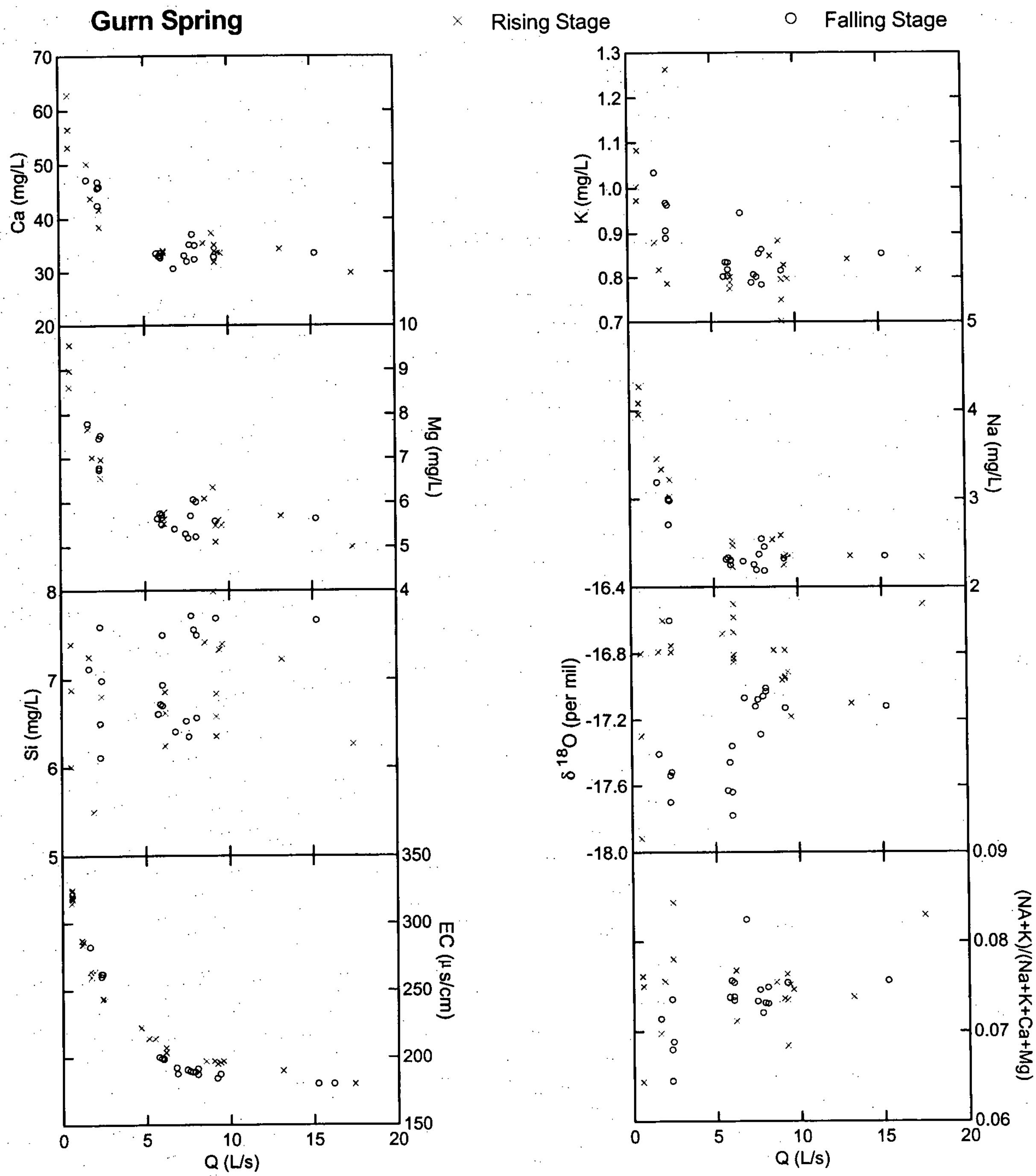

Figure 3.23. Concentration-discharge relations for Gurn Spring. Samples collected on the rising and falling limbs of the hydrograph are represented by the black circles and grey crosses, respectively.

3.6.4 Principal components analysis of water chemistry

Principal components analysis (PCA) of streamwater chemistry was conducted for each of the three study catchments using the following variables: Si, DOC, R_{NA-K}, and EC. Two separate PCA's was performed for Ringrose Slope water chemistry. The first was conducted using all streamwater samples from TH, GB, and GS, while the second was conducted without DOC as a variable but with all streamwater and piezometer samples included. Results are presented in Table 3.8.

For TH streamwater, Factor 1 is composed of EC varying in strong opposition with DOC and R_{NA-K}. The second factor is composed almost entirely of Si. For GB streamwater, Factors 1 and 2 are somewhat different, composed of EC varying in strong opposition with R_{Na-K} (but weakly related with DOC) and Si varying with DOC, respectively. For GS streamwater, Factor 1 is composed of EC varying in opposition with DOC and weakly in opposition with Si, while Factor 2 shows R_{Na-K} and DOC varying together, both in weak opposition with Si.

The first PCA of Ringrose Slope water chemistry showed EC varying in strong opposition with both DOC and R_{NA-K} (Factor 1), and Si varying independently of the other components (Factor 2). The second Ringrose Slope PCA yielded similar results, with EC varying in strong opposition with R_{NA-K} (Factor 1), and Si varying independently (Factor 2).

Table 3.8. Results of PCA of streamwater chemistry from each of the three study catchments. PCA's for Ringrose Slope were conducted using all streamwater samples and Si, DOC, R_{Na-K} and EC as variables (Slope [1]), and using all streamwater and piezometer samples but without DOC as a variable (Slope [2]).

	n		**Component Loadings**				**Eigenvalue**	**% Variance Explained**
			Si	DOC	$R_{NA/K}$	EC		
TH	30	Factor 1	-0.096	0.910	0.795	-0.942	2.357	58.9
		Factor 2	-0.994	0.017	0.016	0.132	1.009	25.2
GB	32	Factor 1	-0.295	0.340	0.883	-0.937	1.860	46.5
		Factor 2	0.801	0.674	0.126	0.111	1.124	28.1
GS	27	Factor 1	-0.469	-0.668	0.365	0.896	1.601	40.0
		Factor 2	0.466	-0.667	-0.806	0.075	1.317	32.9
Slope (1)	89	Factor 1	-0.206	0.943	0.933	-0.973	2.747	68.7
		Factor 2	0.978	0.110	0.099	-0.005	0.979	24.5
Slope (2)	158	Factor 1	0.514		-0.817	0.913	1.767	58.9
		Factor 2	0.843		0.458	-0.064	0.924	30.8

A bivariate plot of Si against R_{NA-K} measured in streamwater and piezometer samples for each of the three study catchments reveals a distinct separation between catchments (Figure 3.24). The data points form a roughly triangular space (outlined in dashed lines) resembling that observed in many diagrams describing a three-component mixing model of water chemistry, such as that employed in many end-member mixing models (EMMA) (Christophersen et al., 1990; Hooper et al., 1990). Potential end members include deep groundwater (high in Si), shallow groundwater (low in Si and R_{NA-K}), and surface water (low in Si, high in R_{NA-K}).

Thickett Creek streamwater (red crosses) and piezometer samples (blue crosses) plotted in the same general area, being relatively low in both parameters. Gurn Brook streamwater plotted towards the far right side of the graph, having the highest values of R_{NA-K} and relatively low Si concentrations. Piezometer samples collected within the GB catchment plotted separately from streamwater samples, being among the lowest in both parameters. Gurn Spring streamwater plotted towards the middle of the graph, having the highest Si concentrations and moderate ratio values. Piezometer samples collected from within the GS catchment plotted in the same general area, however, somewhat above points representing streamwater from GS. Piezometer samples were higher and more variable both for the ratio and concentrations of Si than were streamwater samples from the GS catchment.

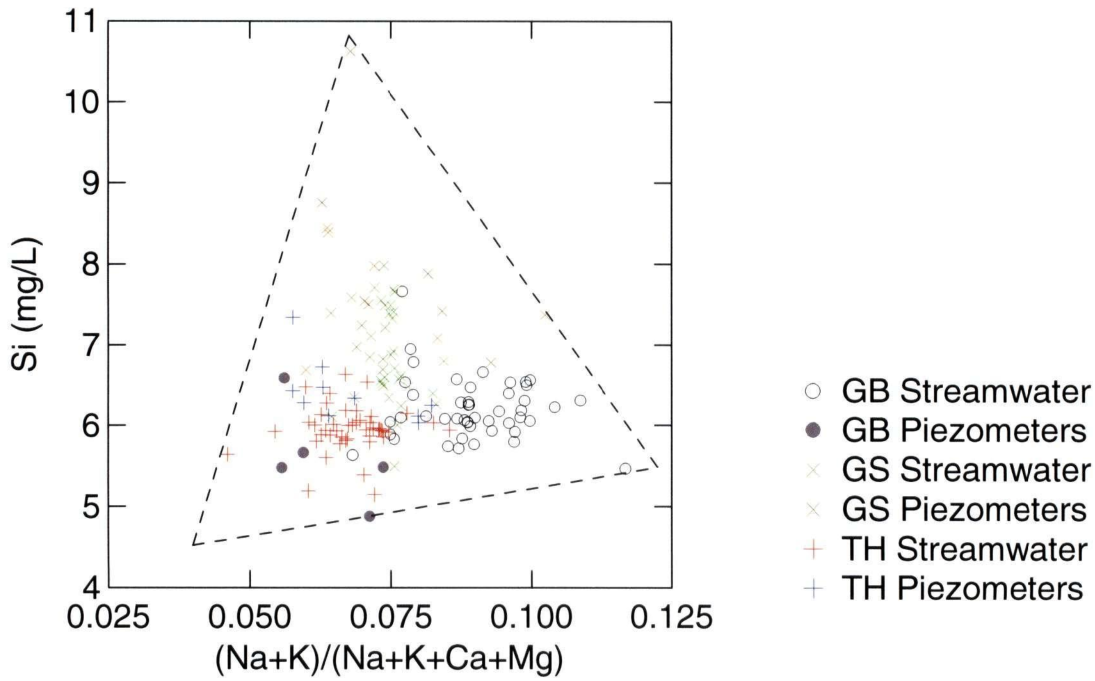

Figure 3.24. Bivariate plot of Silica vs. R_{NA-K}. Samples are grouped by catchment and streamflow samples are distinguished from piezometer samples. The dashed triangle represents a possible interpretation of the plotted data as potential end-members for runoff from Ringrose Slope.

CHAPTER 4
DISCUSSION

This chapter provides an interpretation of results in the context of the specific research question and hypotheses stated in chapter 1. Section 4.1 addresses the validity of a fifth hypothesis: The Gurn Spring catchment receives water from outside the catchment by means of subsurface flow through bedrock fractures. This hypothesis was generated due to results from analysis of historical unit peak flows (Table 3.2) and unit runoff (Figure 3.5), along with analyses of water chemistry data collected during the field season.

Section 4.2 addresses interpretation of temporal sources of catchment runoff, and section 4.3 addresses research question 2 and hypotheses 2 – 4 (Chapter 1, Section 1.3). Section 4.4 discusses implications of the research findings for the hydrological effects of forestry operations, with a focus on forest roads. This section was included to help address the long-term goals of the broader Ringrose Slope study (of which this thesis is a part). Section 4.5 discusses implications of the research finding for catchment scale modelling.

4.1 THE POTENTIAL ROLE OF INTER-CATCHMENT GROUNDWATER FLOW

The GS catchment consistently generated two to three times more unit runoff than both TH and GB despite its relatively low elevation (Table 3.2, Figure 3.5), suggesting inter-catchment groundwater flow into GS through bedrock fractures. This inference is consistent with field observations of fractured rock outcrops on Ringrose Slope and with the deformed nature of the local bedrock as shown in geologic maps (Geological Survey of Canada, 1932). Although there is some uncertainty with respect to the catchment area of TH (see section 2.2.1), GB and GS catchment areas are considered to be relatively accurate and should yield meaningful comparisons between unit runoffs. Comparison of unit runoff amongst these catchments suggests Gurn Spring is receiving water from outside its catchment boundaries (Figure 3.5). The timing of peak flow at Gurn Spring supports the hypothesis of inter-catchment bedrock flow, particularly through large fractures allowing relatively rapid flow. Due to its small size and relatively low elevation, flows were expected to peak on Gurn Spring before those on Thickett Creek and Gurn Brook. However, peak flows in 2002 were synchronous amongst streams despite the lack of snow cover in the GS catchment by that time (Table 3.2, Figure 3.3). Peak flows on Gurn Spring recorded in the majority of previous years were also relatively well synchronized with those on Thickett Creek and Gurn Brook (Table 3.2), suggesting continued meltwater inputs after the disappearance of the snow cover from GS. Alternatively, the observed synchrony of peak flows amongst catchments may be the result of forcing by rainfall/rain-on-snow events.

Streamwater and subsurface water in GS had high concentrations of Si and cations relative to TH and GB, suggesting runoff pathways characterized by long contact times (Figure 3.16, Figure 3.19). A possible explanation is that there exists a soil-water reservoir within GS characterized by a long contact time, and that can be mobilized during periods of high flow. Alternatively, there may be a reservoir of water within the bedrock fracture system that possesses a long contact time, and can be mobilized during periods of high flow. This interpretation supports the inferred existence of inter-catchment transfers of water into Gurn Spring.

Together, these results provide strong evidence of inter-catchment groundwater flow on Ringrose Slope. Bedrock flow has been proposed as the dominant streamflow component in at least one other steep, small headwater catchment, although bedrock in that catchment consisted of sedimentary deposits, particularly sandstones. (Anderson et al., 1997).

While Gurn Spring appears to receive inputs of water from outside its boundaries, the source of this water is difficult to specify. It is possible that the water originated in the upper catchment of Gurn Brook, and flowed through fractures across the northeastern divide of the GS catchment. Despite its high elevations, Gurn Brook produced unit runoff and unit peak flows similar to, and sometimes lower than, those of Thickett Creek (Figure 3.5), consistent with the notion that GB lost water.

4.2 WHAT ARE THE RELATIVE PROPORTIONS OF NEW AND OLD WATER IN STREAMFLOW AND HOW DO THEY CHANGE OVER THE SNOWMELT PERIOD?

4.2.1 Challenges in applying isotopic hydrograph separation

Isotopic concentrations in snowmelt and rainwater vary in both time and space, which generates uncertainty in the "event" water signal and confounds the application of isotopic hydrograph separation (IHS). Most studies have applied IHS to rainfall-dominated catchments (e.g. Buttle and Peters, 1997; Hoeg et al., 2000; Ladouche et al., 2001) or snowmelt dominated catchments of low relief (e.g. Moore, 1989; Maulé and Stein, 1990; Buttle and Sami, 1992), where both the isotopic concentrations and volumes of event waters are relatively uniformly distributed over the catchment, thereby limiting this confounding effect.

The relations between oxygen-18 concentrations in meltwater samples and elevation varied through time, reflecting elevational trends in the initial oxygen-18 concentration of the snowpack, as well as the differences in the timing and rates of snowmelt, which would influence the fractionation process (Table 3.5, Figure 3.14). Oxygen-18 concentrations in meltwater samples exhibited statistically significant increases with time at some sites (Table 3.6, Figure 3.15), consistent with the effects of fractionation during snowmelt. However, the lack of significant relations at three of the eight sampling locations indicates that processes other than fractionation complicated temporal variation in snowmelt isotopic concentrations (e.g. differential mixing between snow-water and rainwater or between distinct layers within the snowpack). This spatial and temporal variability of the event-water $\delta^{18}O$ concentrations, coupled with spatially variable input rates, makes it difficult to apply HIS with any reasonable level of confidence.

Temporal variability in event water isotopic signatures has been addressed in previous studies using the current meltwater $\delta^{18}O$ sampled from snow lysimeters at each sampling time step during the snowmelt period (Maulé and Stein, 1990; Wels et al., 1991; Shanley et al., 2002). However, this method assumes that each meltwater contribution is only stored within the soil until the following sampling occasion (Laudon et al., 2002). Laudon et al. (2002) introduced the runoff-corrected event water approach (runCE) as an alternative means of accommodating temporal variability in the isotopic signature of snowmelt inputs. This method accounts for both the timing and volume of meltwater entering the catchment and the discharge of previously melted and stored water at each time step during the snowmelt period. However, to the best of the author's knowledge, no methods have yet been developed to accommodate the combined spatial and temporal variability in the snowmelt isotopic signal.

4.2.2 Qualitative interpretation of oxygen-18 data

Reasons for the discrepancy between the second streamflow samples collected from TH and GS (Figure 3.19) relative to the first and third are unclear. These samples were submitted to the laboratory at different times and analysed in separate batches. However, the test method employed for all samples was identical and is likely not responsible for the observed discrepancy. This conclusion is supported by the lack of a similar discrepancy in GB streamwater.

Streamwater samples collected during pre-melt base flow were enriched in oxygen-18 relative to early meltwater samples (Figure 3.16). Oxygen-18 concentrations in Gurn Spring pre-melt baseflow were depleted relative to TH and GB. In Thickett Creek and Gurn Brook, isotopic concentrations remained relatively steady throughout the field season (typically ranging from about −16.5 to −17 per mil) despite inputs of significantly more depleted new water early in the melt period, suggesting domination by old water during the early hydrograph rise. Approaching peak flow, the concentration of oxygen-18 in meltwater becomes similar to that in streamwater, thereby limiting further resolution of relative contributions from new/old waters (Figure 3.16).

In Gurn Spring, oxygen-18 increased between the third and fourth samples to levels similar to those in Thickett and GB, then declined in a similar fashion to TH and GB (Figure 3.19). Following peak flow, oxygen-18 concentrations in GS dropped to values similar to those of pre-melt baseflow. It may be that during snowmelt there is mobilization of a reservoir of water having a higher oxygen-18 concentration relative to pre-melt baseflow. One hypothesis is that pre-melt baseflow is supplied by bedrock groundwater having a relatively depleted isotopic signature. During snowmelt, inputs of new water mobilize stored soil-water having a relatively enriched oxygen-18 signature. Following the main melt period, relatively depleted bedrock groundwater again dominates. This two-reservoir model is likely complicated by significant mixing between bedrock groundwater and resident soil water prior to the discharge of bedrock water into the GS stream channel.

4.2.3 Comparison of Results with Other Studies

Concentrations of oxygen-18 in TH, GB, and GS streamwater became increasingly similar to meltwater concentrations sampled from snowmelt lysimeters. On April 14-15, 2002, oxygen-18 concentrations in streamwater and meltwater were nearly identical (Figure 3.19, Appendix D). Other studies employing isotopic hydrograph separation to identify streamflow contributions from old vs. new-water during snowmelt have found considerable differences between concentrations of oxygen-18 in streamwater and meltwater at the time of peak flows, suggesting relatively large old-water contributions at this time (e.g. Moore, 1989). The similar isotopic signatures in streamwater and meltwater during peak flow may suggest high new-water contributions in the three study catchments relative to other snowmelt-dominated catchments described in the literature. However, it could also indicate that the difference between old and new-water isotopic concentrations during peak flow is not sufficiently great to resolve relative peak flow contributions from old and new-water.

4.3 COMPARISON OF STREAMFLOW RESPONSE AND RUNOFF PATHWAYS

4.3.1 Comparison amongst the study catchments

Gurn Brook displayed the flashiest streamflow response of the three catchments, followed by GS and TH, suggesting larger streamflow contributions from deeper subsurface runoff pathways in TH and GS relative to GB. As the snowline progressed upslope, a greater de-coupling of source areas of meltwater from the stream channel is suggested for TH and GS relative to GB. This inference is supported by the shape of streamflow hydrographs (Figure 3.2), comparison of diurnal streamflow response (Figure 3.6), and observed lags between water inputs and streamflow response (Figure 3.7). Snowpack depth has been shown to affect diurnal snowmelt signals and resulting streamflow variations. The role of deep snowpacks in attenuating diurnal melt signals has been well documented (Jordan, 1983). However, peak snow-water-equivalents in the study catchments were low (~ 0.2 m) relative to those measured by Jordan (1.25 m). Because the snowline represents the lowest snow covered area and is characterized by the thinnest snowpack and thus the least snowpack-related attenuation, the role of the snowpack in attenuating snowmelt signals is unlikely to influence the interpretations provided below regarding connectivity between the upslope-moving snowline and stream channels.

The TH channel was the shortest of the three streams, except during the two week period around the time of peak flow when a discontinuous extended channel network coupled with small areas of surface saturation facilitated connectivity between rising source areas of meltwater and the stream channel (Figure 3.10). As the snowline rose above 1000 m (approximately half way up the catchment), the extended channel network receded and source areas became increasingly disconnected from the channel. Though overland flow was observed along roads within TH, this was primarily at lower elevations, suggesting that overland flow along roads did not facilitate connectivity between upslope areas and the channel (Figures 3.11 – 3.13). At all times during the freshet, connectivity between upslope source areas and channel units was maintained primarily through subsurface flowpaths. This resulted in sluggish streamflow response relative to the other streams as noted above, thereby supporting hypothesis #2.

The dominance of subsurface runoff pathways in the TH catchment throughout the freshet is supported by examination of TH groundwater and streamwater chemistry (Figure 3.18, Figure 3.19). Concentrations of Ca, Mg, and EC were elevated during rising stage in TH relative to falling stage at given discharge (Figure 3.20). Other studies have associated clockwise hysteresis amongst rising and falling limbs on plots of groundwater levels vs. streamflow with a threshold in relative streamflow contributions from riparian vs. hillslope areas (Kendall et al., 1999). Kobayashi et al. (1999) observed counter-clockwise hysteresis amongst EC concentrations during a diurnal rise and fall in streamflow in response to a rainfall event in the Moshiri experimental basin and associated this with increasing discharge from shallow flowpaths. Hall (1971) attributed a clockwise hysteresis amongst EC concentrations during rising and falling streamflow in a subcatchment of the Sleepers River watershed to non-random trends in the storage-volume – discharge relation. It is hypothesised that the clockwise hysteresis observed in TH suggests a release of stored subsurface water to the stream channel during rising stage by a process of displacement by relatively dilute snowmelt and rainwater. This is similar to the process of translatory flow originally described by Hewlett and Hibbert (1967), and used to account for the observed proportions of old/new water in several isotopic tracer studies (see review by Buttle, 1994). As the catchment wetted further, the saturated zone thickened, causing saturation overland flow in discrete areas and elevated streamflow contributions from surface/shallow subsurface flowpaths, associated with slightly higher concentrations of DOC, lower EC and cation concentrations, and higher R_{Na-K}. These chemical changes were more evident in GB and GS, probably reflecting the lesser importance of SOF in TH and the greater dominance of deeper subsurface runoff pathways that served to link areas of shallow subsurface flow, surface saturation, and ephemeral channel reaches during periods of high runoff. As streamflow declined following peak flows, the saturated zone thinned and contributions from surface/shallow subsurface runoff pathways dropped, consistent with rising EC and cation concentrations and decreases DOC and R_{Na-K}.

The deeply incised channel of Gurn Brook was the longest of the three catchments and facilitated rapid movement of water between meltwater source areas and the catchment outlet early in the melt period. Though minimal SOF was observed within the catchment, the Gurn Brook channel network expanded both upslope and laterally as the snowline rose, thereby maintaining connectivity between source areas and the stream (Figure 3.10). The extended channel network persisted for some time following peak flows, ensuring that connectivity was maintained within the GB catchment, even when the snowline rose to the upper reaches of the catchment. Throughout the freshet, surface flowpaths (including overland flow along roads) constituted important linkages between upslope source areas and the catchment outlet (Figures 3.11 – 3.13). This resulted in the Gurn Brook displaying the most responsive streamflow of the three catchments throughout the snowmelt period, thereby supporting hypothesis #3.

Contributions from surface and/or shallow subsurface flowpaths appeared to be greater in GB compared to TH and GS, as suggested by the greater difference between streamwater and groundwater chemistry (Figure 3.18) and the greater relative changes in streamwater chemistry associated with peak flows (Figure 3.19). Channel flowpaths (including overland flow along roads) are suggested as the primary surface runoff pathways in Gurn Brook. The lack of observed SOF in GB suggests that subsurface flow is responsible for connecting source areas and the channel network (Figure 3.10). However, streamwater and subsurface water chemistry in the GB catchment suggest that subsurface flowpaths were shorter in that catchment relative to TH and GS (Figures 3.16 and 3.19).

In GS, a higher water table developed in the near-stream riparian corridor relative to near-stream riparian areas in TH (Figure 3.8). Saturation overland flow directly connected to the stream channel was observed in the near-stream riparian area upslope of the weir on Gurn Spring during the three weeks bracketing peak flow (Table 3.4, Figure 3.10). This suggests that streamflow during this period received contributions from SOF linked to the Gurn Spring channel by surface and shallow subsurface flowpaths. The Gurn Spring channel itself was relatively short, although longer than the permanent channel on Thickett Creek, and experienced no observable expansion during the freshet period. Early in the melt period, as the snowline began to rise, the GS channel maintained connectivity between source areas of meltwater and the catchment outlet. As the snowline rose beyond the channel head (i.e. above 725 m), the lack of channel expansion coupled with the near total absence of overland flow along roads resulted in a progressive reduction in connectivity (Figure 3.11 – 3.13).

The specific timing and nature of runoff processes in Gurn Spring remain unclear. Streamwater chemistry suggests that during baseflow conditions, runoff consisted primarily of deep subsurface water having a relatively long contact time (Figure 3.19), such as bedrock groundwater. Soil water, having a relatively enriched isotopic signature, was mobilized as a result of new melt and rainwater inputs and became the dominant streamflow contributor in GS during freshet. This inference is supported by the rise in GS piezometer water levels, particularly in those piezometers located in near-stream riparian positions (Figure 3.7, Figure 3.8, Appendix B) and by time series of oxygen-18 concentrations (Figure 3.19). Water levels in the riparian corridor rose near to the ground surface at this time, producing areas of SOF tightly coupled with the stream channel (Figure 3.8, Figure 3.10). This resulted in greater streamflow contributions from surface and shallow subsurface flowpaths as indicated by increases in streamwater DOC and $R_{Na\text{-}K}$ at this time, reaching their maximum at the time of peak discharge (Figure 3.19). The high unit peak flows in GS relative to TH and GB indicate that transfers of bedrock groundwater into the GS catchment also contributed to streamflow during freshet. Following peak flow, concentrations of all chemical parameters (save perhaps Si) in streamwater returned to near baseflow levels, suggesting that bedrock groundwater again dominated streamflow contributions (Figure 3.19). This two-reservoir model of streamflow generation in GS is consistent with qualitative interpretations of isotopic results. This model is likely complicated by mixing between reservoirs due to bedrock water entering catchment soils prior to being discharged to the stream channel.

4.3.2 Comparison of Results with Other Studies

The study catchments Thickett Creek, Gurn Brook, and Gurn Spring displayed unusually little diurnal streamflow response compared with other snowmelt dominated headwater catchments surveyed from the literature (Kobayashi, 1985; Kobayashi, 1986; Moore, 1989; Buttle and Sami, 1992; Burns and McDonnell, 1998; Shanley et al., 2002). Even the Redfish Upper catchment, located less than 50 km away, displayed significantly greater diurnal streamflow response, despite being forced by similar climatic conditions (Unpublished Data, BC MoF).

The study catchments were the steepest of all the catchments surveyed (Table 3.3), and the strong inverse relation between diurnal response and catchment steepness ($p = 0.005$, $n = 10$) suggests this may be the cause of the study catchments' relatively sluggish diurnal streamflow response, although this notion is counter-intuitive. It may be that relatively flat catchments experience high diurnal streamflow response as a result of one, or both, of the following: (1) synchronized generation of meltwater over a relatively large proportion of the catchment due to uniform energy inputs, and/or (2) increased rate of transfer of water to the stream channel due to the development of widespread saturation overland flow. In a study by Kim et al., (in press) in the upper Gray Creek catchment, British Columbia, comparisons were made between diurnal variations in streamflow and water table elevations (measured at 5 min intervals). Results showed that throughflow can be sufficiently rapid to produce diurnal streamflow response during snowmelt, particularly if the water table rises into more permeable shallow soil layers. This process of transmissibity feedback was observed by Kendall et al. (1999) in the W9 sub-catchment of the Sleepers River watershed and was associated with an abrupt increase in streamflow with a rise of the water table into near-surface zones of high transmissivity. Flatter catchments are more likely to experience widespread elevation of the saturated zone into more conductive soil layers and an associated throughflow-induced diurnal response. Steep catchments such as those on the Ringrose Slope may have such limited areas capable of producing saturation overland flow and rapid throughflow that response is dominated by relatively more sluggish subsurface flow paths, particularly when the meltwater source becomes disconnected from the channel network.

4.4 IMPLICATIONS FOR THE HYDROLOGICAL EFFECTS OF FOREST HARVESTING AND ROAD CONSTRUCTION

This section briefly discusses the implications of the research findings for the hydrological effects of forest harvesting (section 4.4.1) and road construction (section 4.4.2). The hydrological effects of forest harvesting and road construction constitute a field of research in forest hydrology in and of themselves, and a detailed evaluation of these effects is beyond the scope of this thesis.

4.4.1 *Forest harvesting*

The specific impacts of forest harvesting on the TH, GB, and GS catchments would depend largely on the type of harvesting prescribed. However, previous studies indicate that increases in the magnitude and timing of peak flows would result in all catchments, as would increases in annual water yield and summer low flows (Harr et al., 1982; Troendle and King, 1985; Hetherington, 1988; Van Haveren, 1988). The magnitude of these increases would depend on the area harvested.

In Thickett Creek and Gurn Brook, the channel network was observed to expand in response to increasing water inputs, suggesting that increases in annual water yield and the magnitude of peak flows could lead to greater expansion of the channel network. This could result in longer and more continuous extended channel networks during peak flow in the TH and GB catchments, respectively. In both catchments, this would increase connectivity between source areas and the catchment outlet producing flashier streamflow response.

Increased low flows in Gurn Brook might lead to measurable flows at the weir throughout the summer months. In Gurn Spring, no expansion of the channel network was observed in response to increasing water inputs. This suggests that increases in annual water yield and the magnitude of peak flows would not lead to an expansion of the channel network. Consequently, no change in the responsiveness of Gurn Spring streamflow would result.

If the hypothesis that GS receives inter-catchment transfers of bedrock groundwater from GB is true, then the effect of forest harvesting in Gurn Brook's upper catchment may not show up fully as a change in GB streamflow measured at the weir: some of the increased runoff could end up discharging via Gurn Spring. This could complicate interpretation of the results of a paired-catchment analysis of harvesting in the GB catchment.

4.4.2 *Road construction*

The hydrologic effects of forest roads and road construction have received significant attention in the literature (e.g., Megahan, 1972; Beschta, 1978; Wemple et al., 1996). The impact of road construction at Ringrose Slope would depend on the density of roads and compacted areas within the study catchments, as well as the spacing of drainage-relief culverts. Road construction would likely result in increased interception of subsurface waters and the generation of rapid overland flow along road segments. This would increase streamflow contributions from surface flowpaths and connectivity between source areas and channel units, thereby reducing lag times and increasing catchment responsiveness. This would likely be most pronounced in Thickett

Creek, where deep subsurface flowpaths dominate throughout the catchment. The effect would be least pronounced in Gurn Brook at lower and middle elevations, where deep subsurface flowpaths constitute a less important source of streamflow generation relative to channel flow.

Construction of forest roads that cross drainage boundaries could further facilitate the inter-catchment transfers of water along surface flowpaths, thereby complicating the processes currently responsible for the movement of water between catchments. This would also result in some catchments losing water and thus experiencing reduced annual water yield, with water yield increases in receiving catchments. In an extreme scenario, roading could result in sufficient transfers of water out of a catchment to render it dry during low-flow periods.

Culverts and cross-ditches constructed during road construction would result in lateral concentrations of flow along slopes. This would increase soil erosion at discrete locations thereby increasing the potential for mass wasting and landslide events. This is particularly true where slope gradients are highest, such as at lower and middle elevations and near channel units within the GB catchment. Increased rates of sedimentation might also result following mass wasting events or during road construction itself.

From a management perspective, these impacts might be considered insignificant or manageable. However, water supply licenses have been issued for all three of these streams, with Thickett Creek and Gurn Spring currently being used as primary supplies of drinking water. Changes in their flow regimes could have significant impacts on local residents who currently depend on these streams for water supply. Assuming no significant alteration of the channel networks as a result of harvesting activities and road building, nothing in the preceding discussion suggests that forest harvesting would have adverse effects on water supply in these streams. If anything, increased low flows during summer months in Gurn Brook, currently the only one of the streams not used as a domestic water supply, could make it more suitable for this purpose. However, the potential for cross-drainage transfers between catchments along road segments is high, as evidenced by field observations of overland flow along existing roads crossing the TH and GB catchment boundaries. However, the potential impacts of forest roads on cross-catchment drainage are minimal relative to the significant inter-catchment transfers of bedrock groundwater into Gurn Spring.

The above discussion focuses exclusively on impacts to the magnitude and timing of water supply, and does not consider the potentially adverse effects of forest harvesting and road construction on water quality.

4.5 IMPLICATIONS FOR CATCHMENT SCALE MODELLING

Hydrologic models such as TOPMODEL and the distributed hydrology-soil-vegetation model (DHSVM) treat the soil-bedrock interface as an impermeable boundary, confining runoff processes to the overlying soils and surface environment. Such models are inherently incapable of representing runoff processes and hydrologic response in catchments that experience significant flow through the bedrock itself, particularly if this leads to inter-catchment transfers of water. The existence of inter-catchment subsurface flow through bedrock fractures on Ringrose Slope has been suggested in the above discussion. This calls into question the appropriateness of existing catchment-scale models for representing hydrologic response in similar catchments and areas underlain by fractured parent material. It further highlights the need for models that allow parameterization of the underlying bedrock (e.g. considering it as an extension of the soil profile) and are capable of simulating transfers of water across drainage boundaries.

CHAPTER 5
CONCLUSIONS

5.1 SUMMARY OF FINDINGS

This thesis set out to identify: (1) the relative proportions of pre-event and event water in TH, GB, and GS streamflow and how these proportions varied throughout a freshet period, and (2) the dominant runoff pathways in each catchment and how they varied throughout the freshet. It was hypothesised that differences in streamflow response would be related to the degree to which connectivity between the channel and meltwater source areas was maintained as the snowline progressed upslope. It was further hypothesised that this would result in Thickett Creek displaying the least responsive streamflow, followed by Gurn Spring, with Gurn Brook displaying the flashiest response of the three streams.

Application of traditional IHS to identify old vs. new water contributions was unsuccessful due to an inability to adequately characterize the volumes and isotopic signature of the new-water component. This was due largely to significant temporal and spatial variation in meltwater isotopic concentrations, particularly in relation to elevation. However, qualitative interpretation of oxygen-18 data suggest relatively large old-water contributions in all catchments, at least during the early portion of the seasonal hydrograph rise. The similarity between streamwater and meltwater isotopic concentrations at the peak of the freshet is not consistent with results from other isotopic tracer studies in snowmelt dominated catchments, and makes it impossible to resolve the relative contributions of old and new water.

In Gurn Spring, oxygen-18 concentrations actually shifted away from the new-water concentrations in the early stage of freshet. It is hypothesized that this shift resulted from the mobilization of a reservoir of relatively enriched water, likely stored within the soil.

Deep subsurface runoff pathways dominated the TH catchment throughout the 2002 freshet, with minimal surface/shallow subsurface flow contributions during peak flow. In contrast, Gurn Brook was dominated by channel flow throughout the snowmelt period, with relatively short subsurface flowpaths maintaining linkages between upslope source areas and the stream channel. Runoff processes in Gurn Spring likely reflect a system composed of at least two reservoirs: bedrock groundwater, and soil water. Bedrock groundwater dominated streamflow contributions during baseflow, with isotopically enriched soil water dominating during freshet. Bedrock groundwater again dominated streamflow in GS during hydrograph recession. The suggested model is likely complicated by mixing between reservoirs due to bedrock water entering catchment soils prior to being discharged to the stream channel.

Results support the four hypotheses originally stated. Streamflow in TH was least responsive of the catchments, followed by GS and GB. In TH, this resulted from the disconnection between meltwater source areas and the channel as the snowline moved upslope. This de-coupling was less pronounced in GS, resulting in moderately responsive streamflow relative to TH and GB. In GB, expansion of the channel network ensured that connectivity between source areas and the channel was maintained to a greater degree than in the other catchments, resulting in the flashiest streamflow response. Differences in catchment streamflow response are clearly related to the degree to which connectivity between channels and source areas is maintained as the snowline rises.

The potential hydrologic impacts of forest harvesting within the study catchments are likely of minimal concern from a management perspective. The main risk is associated with cross-catchment water transfers as a result of subsurface flow interception at road cuts and transfer across catchment divides within the road drainage system. However, care must be taken with respect to any future harvesting and roading operations to avoid impacting drinking water supplies to local residents.

5.2 Recommendations for Future Research

The hydrogeomorphic concept is a promising framework for the investigation of catchment streamflow response as a function of temporal and spatial variation in the attributes of catchment runoff processes and pathways, and in connectivity between hydrogeomorphic units. Previous studies have mainly employed the hydrogeomorphic concept to investigate hydrologic response from temporally variable rainwater inputs, safely assuming little or no spatial variation in rainwater inputs (Sidle et al., 2000; Hangen et al., 2001; Ladouche et al, 2001). This study has benefited from the unique opportunity to investigate the effect of contrasting catchment geomorphologies on streamflow response during snowmelt. Further, it illustrates how streamflow response in steep snowmelt-dominated catchments is affected by spatial variation in water inputs (i.e. from the effect of elevation on snow accumulation, snowmelt, and rainfall). Studies employing the hydrogeomorphic concept to examine streamflow response in such catchments should seek to address this issue. As the concept focuses on linkages between hydrogeomorphic units, studies should endeavour to determine the degree to which connectivity between upslope areas and stream channels is maintained as the snowline moves upslope. This study employed a combination of snowline mapping, piezometer measurements, and field observations of surface flow towards this end.

This study highlights the need for improved models for conducting IHS for catchments in which the rates and isotopic concentrations of event water vary significantly both spatially and temporally. Further research should examine the role of groundwater flow in bedrock fractures in the context of headwater catchments, particularly the potential for contributing to peak flows as well as base flow. Few studies of headwater catchments have examined fractured bedrock flow in detail; Anderson et al. (1997) is a notable exception. In particular, the study calls into question the appropriateness of existing catchment-scale models for representing hydrologic response in catchments underlain by fractured bedrock, where significant flow might occur through the fracture network, given that most models assume the bedrock to be impermeable. There is need for research focused on the development of parameterizations of the underlying bedrock (e.g. considering it as an extension of the soil profile) that are capable of simulating transfers of water across drainage boundaries. Given that hydrologic models are likely to be used with increasing frequency in the near future as a tool for managing the hydrologic effects of land use (e.g., forestry), predictions of such models will only be credible if they can accurately represent all of the dominant processes.

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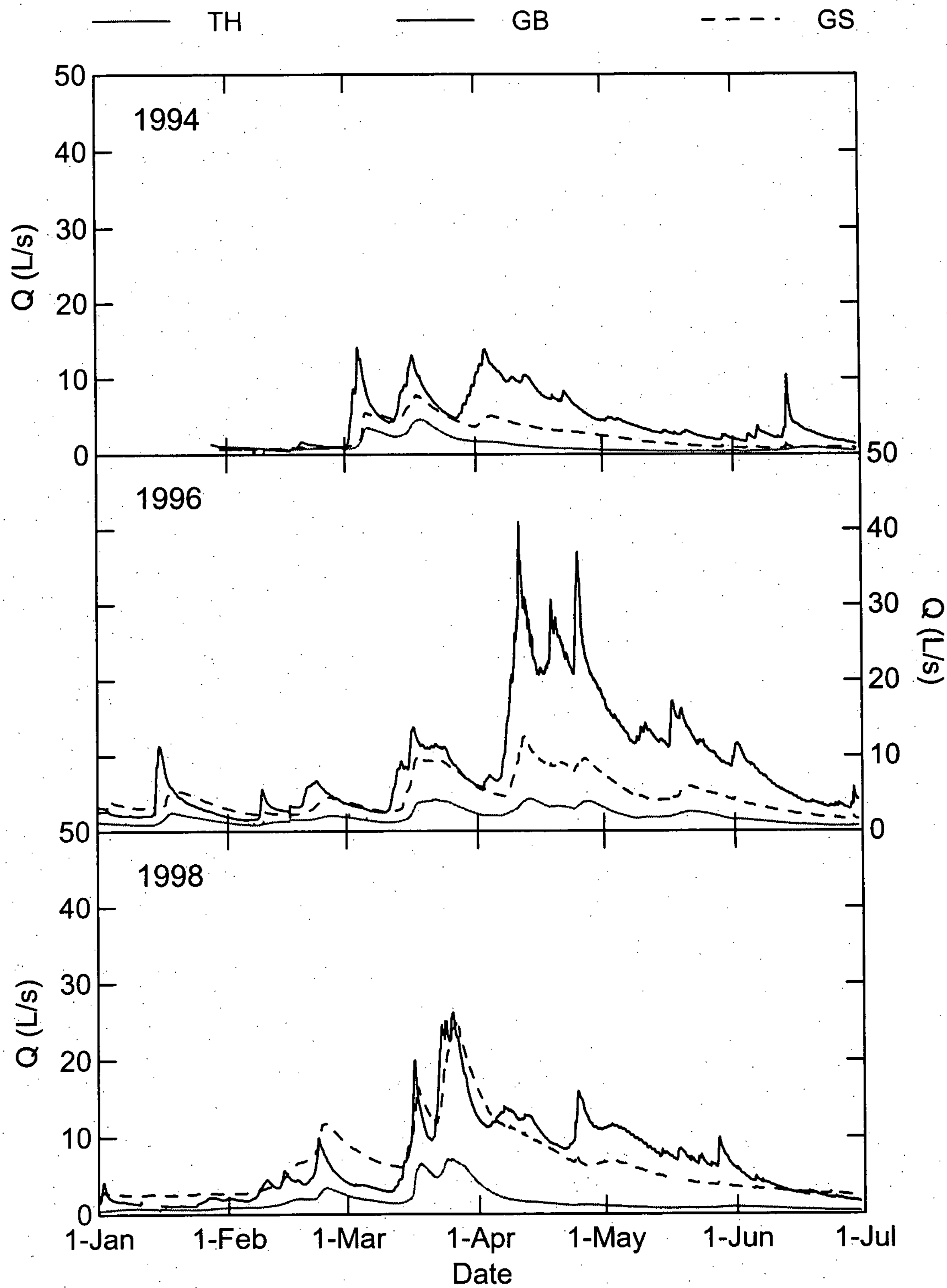
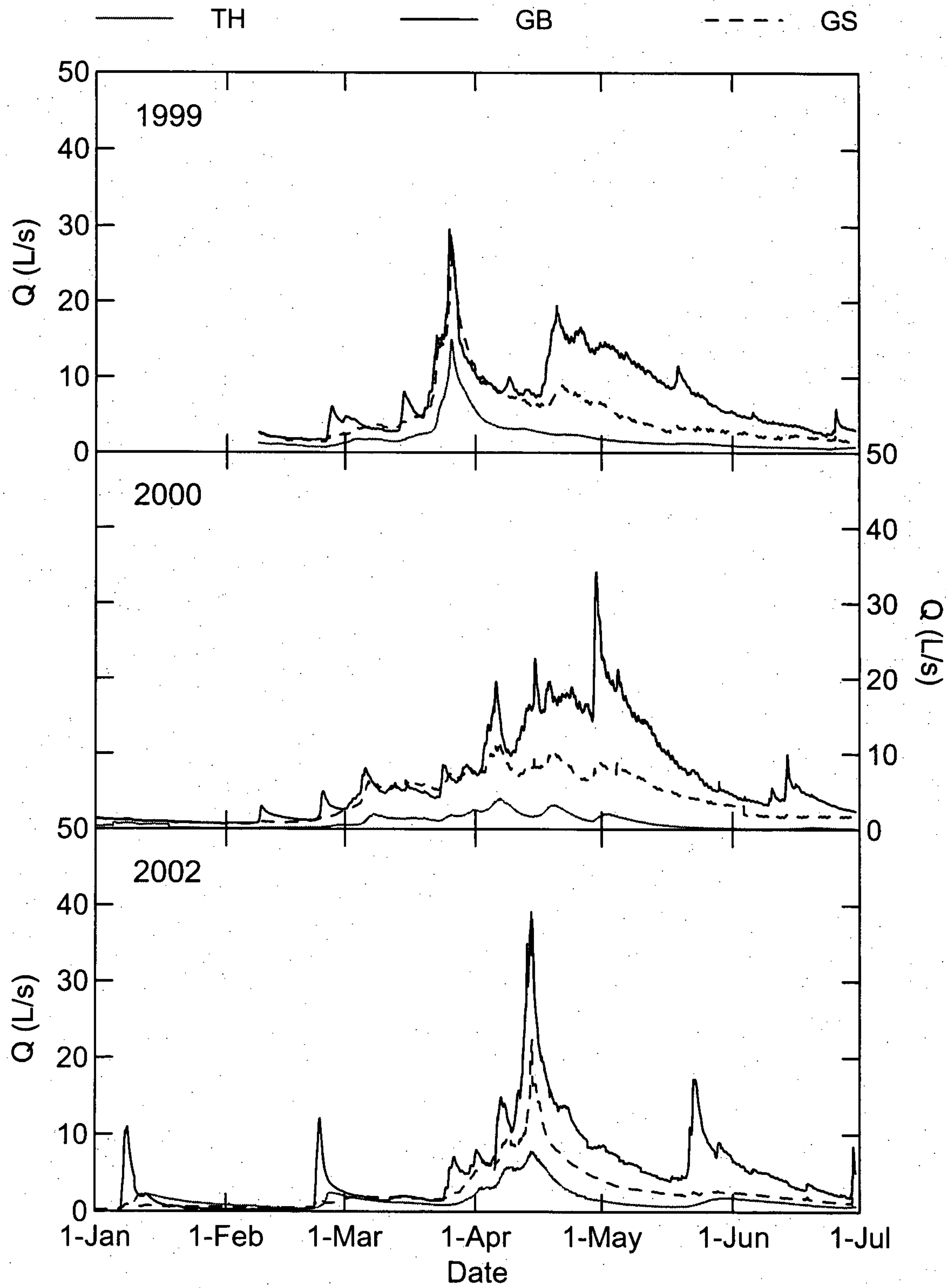
APPENDIX A

FRESHET HYDROGRAPHS

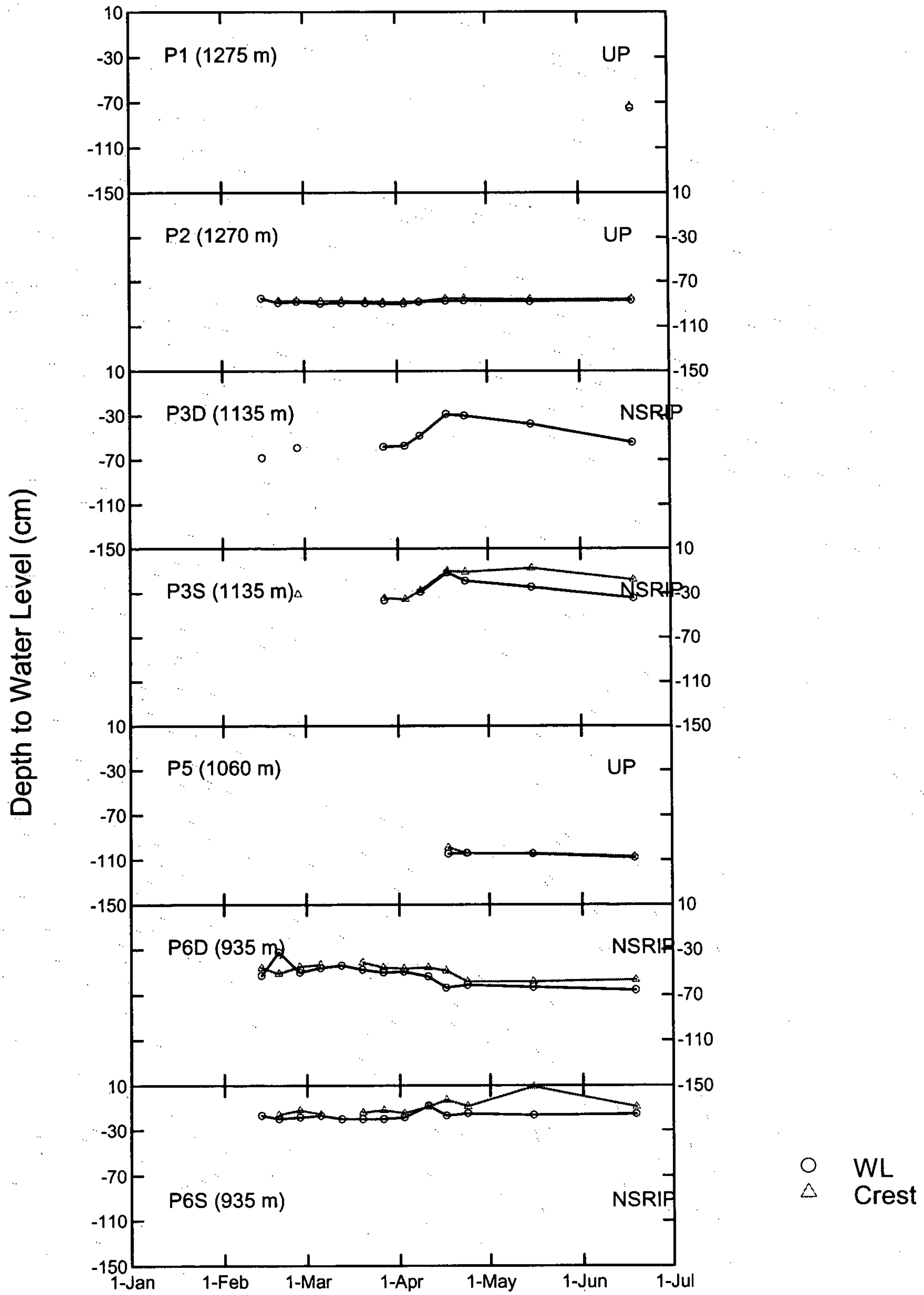


TH
GB
GS
1994
1996
1998
Q (L/s)
0
10
20
30
40
50
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
Date

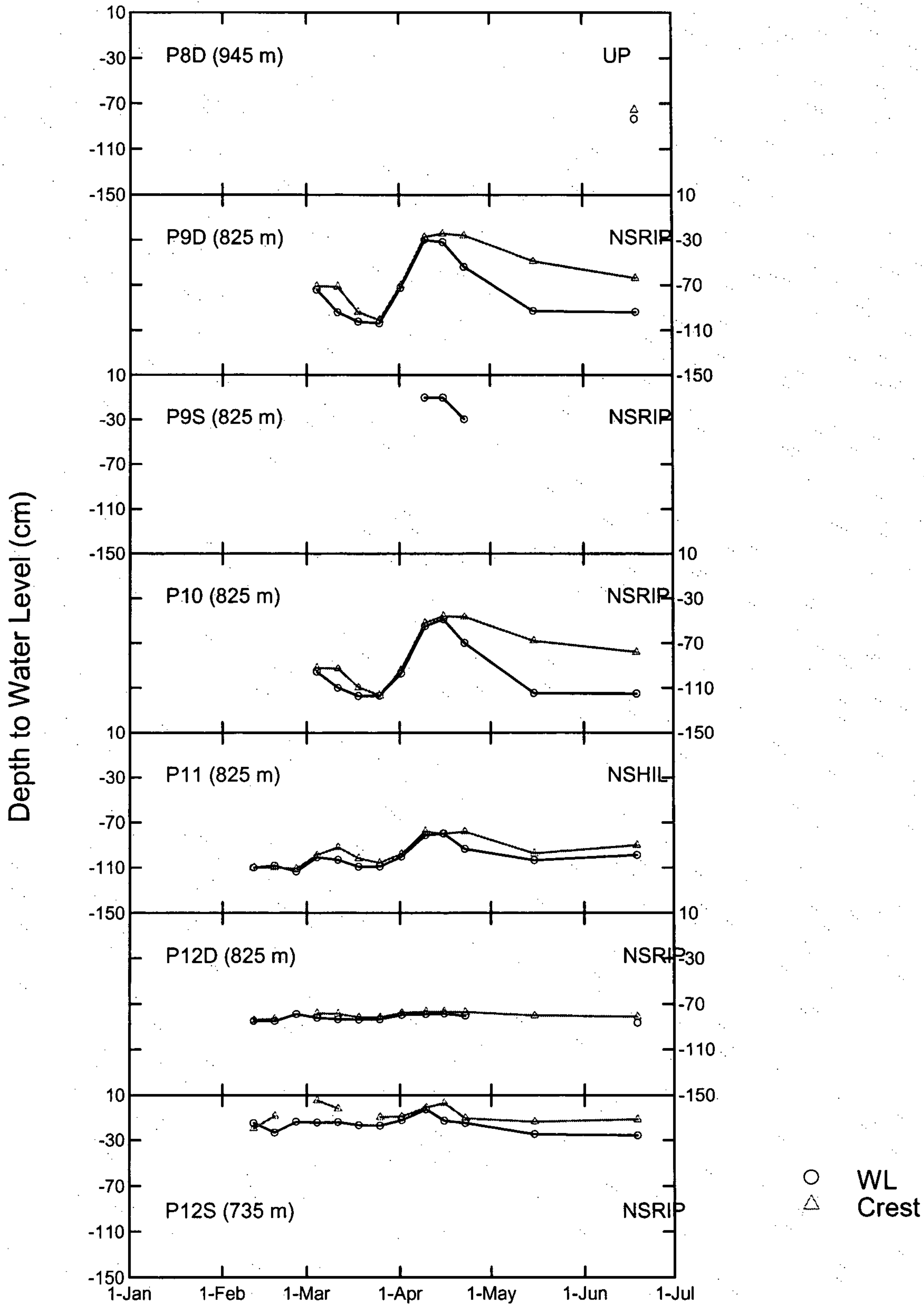

TH
GB
GS
1999
2000
2002
Q (L/s)
Q (L/s)
Q (L/s)
0
10
20
30
40
50
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
Date

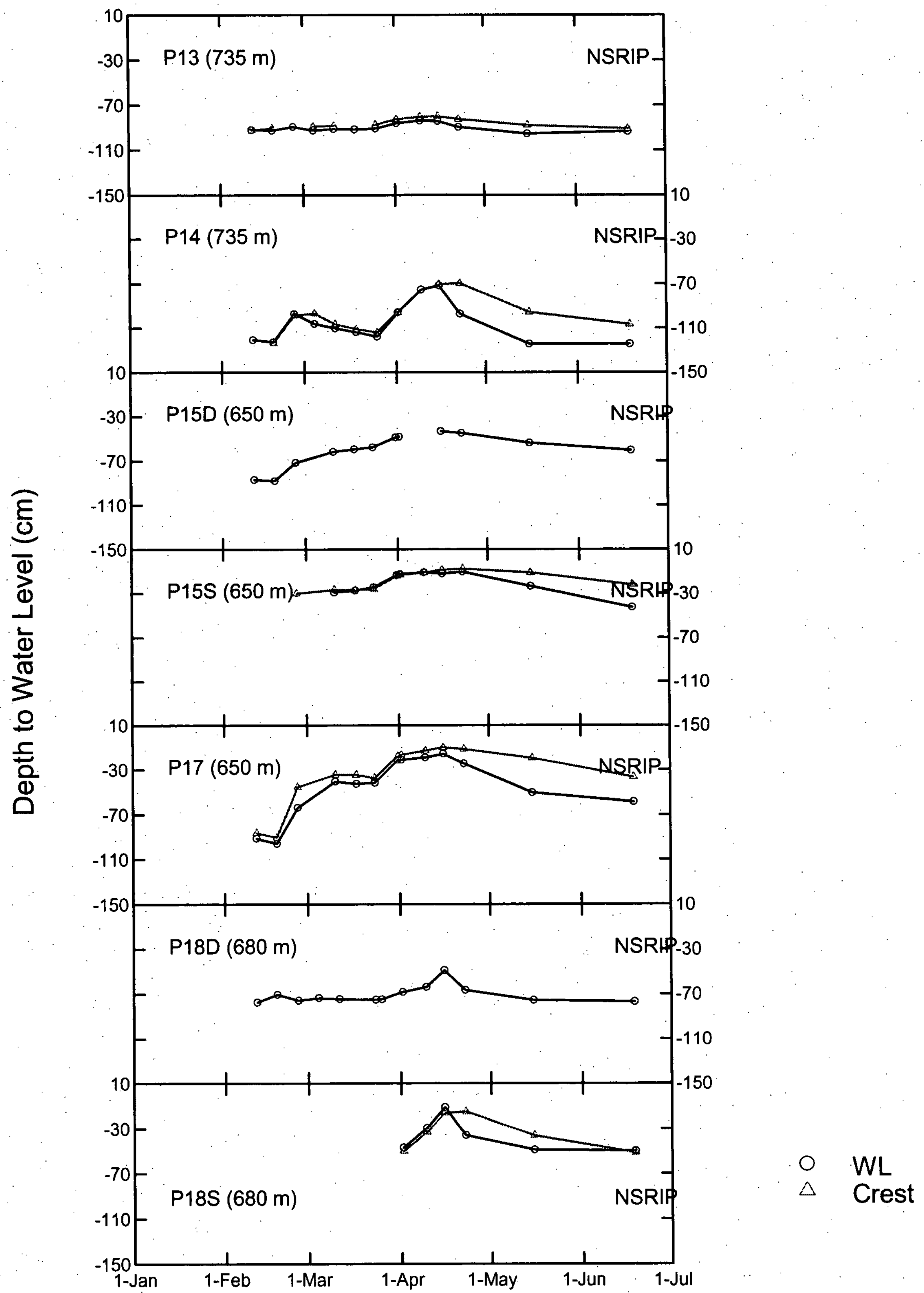
APPENDIX B

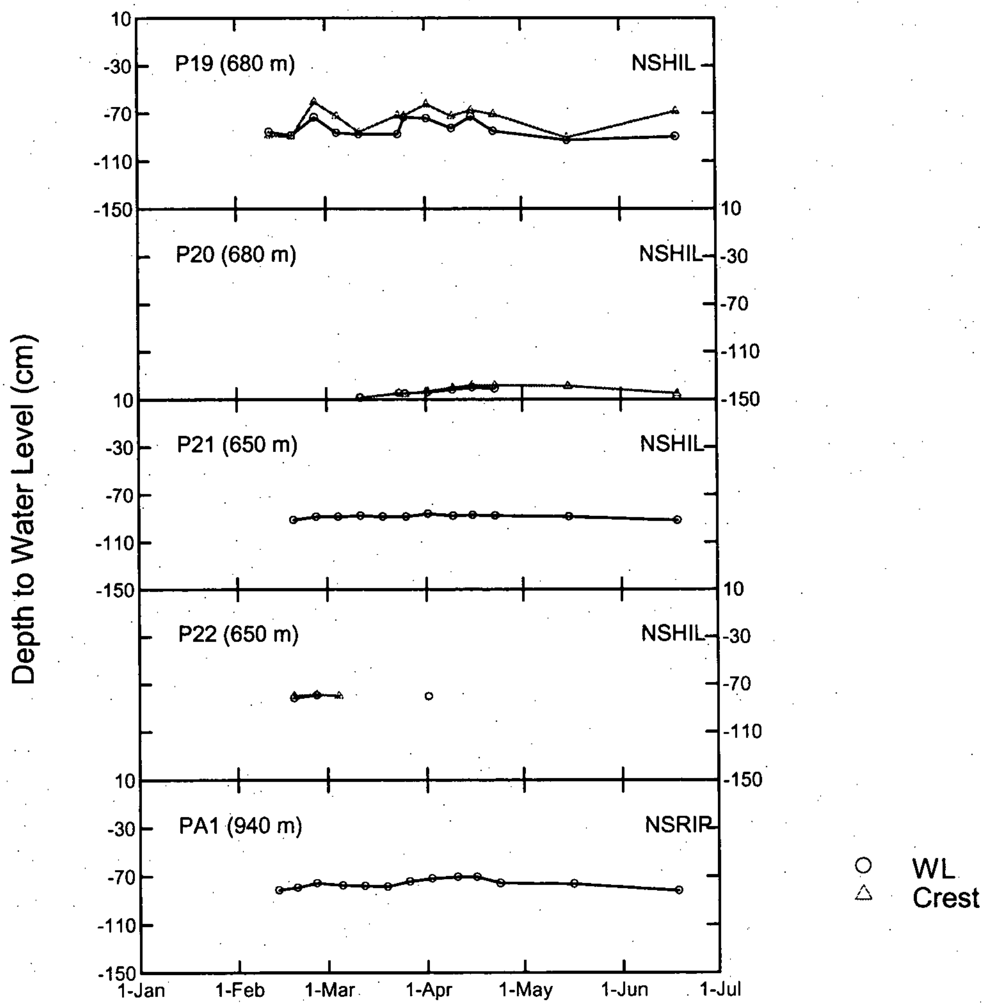
PIEZOMETER WATER LEVELS AND CREST DATA



P1 (1275 m)
UP
P2 (1270 m)
UP
P3D (1135 m)
NSRIP
P3S (1135 m)
NSRIP
P5 (1060 m)
UP
P6D (935 m)
NSRIP
P6S (935 m)
NSRIP
Depth to Water Level (cm)
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
WL
Crest


Depth to Water Level (cm)
P8D (945 m)
UP
P9D (825 m)
NSRIP
P9S (825 m)
NSRIP
P10 (825 m)
NSRIP
P11 (825 m)
NSHIL
P12D (825 m)
NSRIP
P12S (735 m)
NSRIP
10
-30
-70
-110
-150
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
WL
Crest


P13 (735 m)
NSRIP
P14 (735 m)
NSRIP
P15D (650 m)
NSRIP
P15S (650 m)
NSRIP
P17 (650 m)
NSRIP
P18D (680 m)
NSRIP
P18S (680 m)
NSRIP
Depth to Water Level (cm)
10
-30
-70
-110
-150
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
WL
Crest



Depth to Water Level (cm)
P19 (680 m)
NSHIL
P20 (680 m)
NSHIL
P21 (650 m)
NSHIL
P22 (650 m)
NSHIL
PA1 (940 m)
NSRIP
10
-30
-70
-110
-150
1-Jan
1-Feb
1-Mar
1-Apr
1-May
1-Jun
1-Jul
WL
Crest

APPENDIX C

OBSERVATIONS OF SATURATION OVERLAND FLOW

What follows is a detailed description of overland flow observed throughout the field season. Occurrences of SOF are numbered according to the order in which they were observed and can be cross referenced with both Figure 3.10 and Table 3.4.

1. On a broad forested hillslope where overland flow began as a seep in the cavity left by the roots of a wind-thrown tree and continued downslope for a number of meters. It was observed on Feb 25, 2002 and its location was estimated to be just below 900 m and immediately north of the Thickett Creek catchment[1].
2. In the near-stream riparian area surrounding the lower transect of piezometers on Gurn Spring (P15s, P15d, P16, and P17) on Mar 31, 2002. This was primarily due to the formation of a short, intermittent channel on the flat valley bottom that roughly paralleled the primary channel of Gurn Spring. Commencing as heavy seepage from a large macropore in the ground upslope of P17, it ran downslope for 10-20 meters, passing within roughly 2 m of P17 before rejoining the main channel downstream of the piezometers. Diffuse surface saturation and overland flow were observed between this new secondary channel and the main channel This was traced upslope to an area of localized spillage at a bend in the main channel.

In addition to the flows observed prior to the beginning of April (#1-2, above), SOF was observed between Apr 9-10, 2002 in the following locations:

3. On Apr 9, 2002 in two small valley features running parallel to each other immediately off a switchback in the road at 825 m and just north of the Thickett Creek catchment. Channelized flows were observed in each of these micro-valley features, both generated by seepage immediately upslope. One of these micro-channels passed adjacent to P9s and P9d so that those piezometers were within centimetres of the surface water.

[1] Locations of observed SOF were not surveyed precisely and are derived from field approximations using local topographic features, roads, and instrument locations (e.g. surveyed piezometers and climate stations).

4. On the broad forested hillslope within the Thickett Creek catchment at approximately 900 m where a micro-channel had formed by seepage in an area of short (1-2 m) convergent hillslopes. SOF was first observed in this location on Apr 10, 2002.
5. Also on the broad forested hillslope within the Thickett Creek catchment at approximately 925 m where a seep occurred approximately 10-25 m downslope of the piezometer A1 causing downslope surface saturation. SOF was first observed here on Apr 10, 2002.

The most widespread occurrence of SOF was observed immediately following peak streamflows during the period Apr 15-18, 2002. During this period, SOF persisted in each of the locations discussed above. New occurrences of SOF were observed in the following locations:

6. On Apr 15, 2002 intersecting the road just below 950 m where a small channel of overland flow emerged from a shallow gully feature vegetated by herbaceous shrubs and brush.
7. On Apr 15, 2002 above the road just below 775 m where a saturated surface conditions had developed upslope of the road-cut. This was judged to be located just within the TH catchment.
8. On Apr 15, 2002 below the road and almost directly across from #7 (above) and upslope of the weir on Thickett Creek where large quantities of SOF emerged from multiple seeps. From these, overland flow continued in a series of intermittent seeps and saturated areas down to the permanent channel of Thickett Creek.
9. On Apr 16, 2002 at approximately 910 m and upslope of #4. SOF occurred here as an intermittent micro-channel in an area of short (1-2 m), low angled convergent hillslopes. SOF observed between 900 m and 925m appeared to be connected by subsurface flows linking the observed seeps and micro-channels (i.e. linking #4, 5, and 8).
10. On Apr 16, 2002 in the forest at approximately 875 m where seepage emerged and continued a short ways downslope before disappearing.
11. On Apr 16, 2002 immediately adjacent to the road switchback at 825 m, where flows from the two micro-channels observed on Apr 9-10, 2002 (#3) had extended 10-20 m further upslope.

It is possible that the SOF observed on Feb 25, 2002 actually occurred within the Thickett Creek catchment.

12. On Apr 16, 2002 just below #3 where the two micro-channels converged downslope of P9s and P9d.
13. On Apr 17, 2002 at approximately 1175 m within the Gurn Brook catchment upslope of P3s and P3d where seepage commenced on a narrow terrace feature located along a forested north-facing hillslope. From here seepage continued downslope along the terrace for approximately 10-25 m.
14. On Apr 18, 2002 within the TH catchment and intersecting the road just below 825 m where a small channelized feature emerged from the forest. The micro-channel was traced 10-20 m into the forest to its source at an area of small convergent hillslopes producing localized seepage.
15. On Apr 18, 2002 emerging as a large seep from directly beneath the base of a tree just below the road at approximately 800 m within the TH catchment. Flow continued into the forest for 10-25 m before ponding somewhere upslope of the road just above 825 m.

Though not as widespread as the week prior, SOF persisted in a number of locations during the period Apr 22-24, 2002. These were: #1, 2, 10, 12, 13, and 14 (above). In addition, SOF was observed in significantly diminished quantities at #8 and 15 (above).

SOF was mapped a final time on May 15-16, 2002, at which time overland flow persisted only in diminished quantities at #8 and 15 (above). New SOF was observed in the following location:

16. On May 15, 2002 in the GB catchment and emerging from a forested gully with steep sidewalls upslope of the road just above 1125 m. Flows were observed crossing the road and continuing into the forest below.

APPENDIX D

ISOTOPIC CONCENTRATIONS IN MELT AND RAINWATER

Oxygen-18 measured in water collected from melt samplers. Samplers were designed to collect integrated samples of melt and rainwater.

		Date													
Lysim.	Elev. (m)	Mar 13	Mar 24	Mar 25	Mar 26	Mar 27	Apr 2-3	Apr 5	Apr 8	Apr 10	Apr 14	Apr 17	Apr 18	Apr 19	Apr 23
		$\delta^{18}O$													
L1	1275									-18.89	-17.33	-19.19		-17.75	-16.33
L2	1270				-20.38		-18.86	-17.77	-18.15	-19.12	-17.5		-19.68	-17.77	-17.31
L3	1135		-21.45		-20.99	-20.51		-18.35	-18.56	-18.1	-16.9	-17.89		-17.16	-16.58
L5	1060		-21.03		-20.9	-20.47		-19.14	-17.99	-17.36					
L6	935	-20.3	-21.51		-20.7	-19.79		-16.71	-18.02	-17.47					
L8	945		-20.99		-21.05	-20.09	-18.85		-18.1	-18.4					
L9	825		-21.48	-21.12		-18.29		-16.24	-16.31	-16.1					
L15	655	-19.7	-21.7	-21.28		-19.25									

Oxygen-18 measured in rainwater collected from snow-free melt samplers.

		Date		
Lysim.	Elev. (m)	Apr 14	Jun 18	Jun 20
		$\delta^{18}O$		
L1	1275			-18.77
L5	1060	-15.95		
L6	935	-15.7		
L8	945	-15.77		-18.27
L9	825	-14.29		
L15	655	-14.4	-19.97	