Rainfall-Runoff Hydrograph Characteristics in a Discontinuous Permafrost Watershed and Their Relation to Ground Thaw

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**Abstract**

Rainfall-runoff hydrographs were analyzed for 49 rainstorms over 5 years in a 7.6 km² alpine discontinuous permafrost watershed to assess the effect of seasonal thawing on hydrograph parameters. Hydrographs were analyzed for 11 common characteristics including runoff ratio, initial abstraction, recession coefficient, and several parameters related to shape of the hydrograph. Runoff ratios varied between 0 and 0.33 (average 0.09) and declined throughout the summer, reflecting increased active layer storage. Hydrograph recessions were steeper immediately post-freshet and flattened as the summer progressed, as flow pathways descended into soils with lower transmissivities. There was no relation between antecedent wetness and timing response, indicating that saturated areas of the catchment exist near the stream throughout the season, facilitating rapid runoff. Results indicate that at this scale, permafrost and active layer depth exert a strong influence on the stormflow hydrograph.

**Keywords:** discontinuous permafrost; hydrograph analysis; hydrology; recession; runoff.

**Introduction**

Watersheds underlain with discontinuous permafrost show a high degree of spatial variability in the timing and magnitude of hydrological processes (Carey & Woo 2001a, Spence & Woo 2003). Due to the relatively impermeable nature of permafrost, percolation is restricted and the soil storage capacity reduced, resulting in greater volumes of event water (both meltwater and rain) being conveyed to the stream from perched unconfined aquifers (Quinton & Marsh 1998, Carey & Woo 2001b). Following snowmelt, thaw of seasonally frozen ground increases the thickness of the active layer, enhancing basin storage and altering flow pathways (Bowling et al. 2003, Carey & Quinton 2004). As the ground thaws, the water table descends into deeper soil layers with reduced saturated hydraulic conductivity, stormflow response is dampened. In contrast, catchment areas without permafrost infiltrate and percolate meltwater and rainwater to the deeper regional groundwater table without generating significant lateral flow.

Rainfall-runoff events in permafrost basins are flashy, with accentuated peaks, extended recessions, and low baseflow contributions (Dingman 1973, McNamara et al. 1998). The mechanisms of runoff production in permafrost catchments has emphasized rapid surface and near-surface flow in porous organic soils that are ubiquitous surface cover, preferential flow pathways through interconnected surface depressions, soil conduits, and rills, particularly during the snowmelt period (Hinzman et al. 1993, McNamara et al. 1998, Quinton & Marsh 1999, Carey & Woo 2001a). As the active layer thaws and the saturated layer descends, rapid runoff declines and these runoff pathways become less effective in conveying water to the drainage network. In addition to changes in vertical soil hydraulic properties, the areal extent of runoff generation declines following snowmelt. When the saturated layer resides within near-surface organic soils, water from slopes and upland areas can be conveyed rapidly to the stream and the source area for runoff generation is relatively large and the basin is highly connected. However, as the water table drops into the mineral substrate, hill slopes and areas away from the stream become disconnected, reducing the contributing source area (Carey & Woo 2001b). The total percentage of the basin underlain by permafrost is important as seasonally frozen soils have predominantly vertical water flux throughout the year, and basin comparison studies in zones of discontinuous permafrost reveal significant differences in streamflow properties and hydrochemistry based upon permafrost disposition (McLean et al. 1999, Petrone et al. 2007).

A significant amount of research in discontinuous permafrost environments has investigated runoff mechanisms at the hillslope or plot scale (Carey & Woo 2001b, Spence & Woo 2003). This process information has not been linked to larger scale basin flow attributes. For example, in a continuous permafrost environment, McNamara et al. (1998) studied temporal variations in runoff properties over a cascading range of watershed scales and related hydrograph characteristics to the influence of permafrost. A similar exercise in discontinuous permafrost environments would provide validation that processes operating at small scales are manifested in the streamflow hydrology at the basin scale.

Hydrograph analysis continues to be a widely utilized and practical assessment tool of basin storages and in the calibration of many hydrological models (i.e. Tallaksen 1995, Szilagyi & Parlange 1998). Response times, runoff ratios and recession parameters provide first-order information as to catchment functioning. In this regard, hydrograph analysis remains a useful tool to evaluate whether conceptual and
numerical models of runoff generation derived from plot and slope studies are applicable to the entire catchment, which integrates areas of seasonal and permafrost soils. It is the objective of this paper to evaluate five years of summer stormflow data to improve understanding of how heterogeneous discontinuous permafrost basins deliver water to the stream. Hydrograph parameters will be compared with precipitation characteristics and antecedent conditions such as flow and time of year (as a surrogate for ground thaw). The influence of increased basin storage on rainfall-runoff relations will be determined and results compared with knowledge of processes at smaller scales. The snowmelt period will not be considered.

**Study Area**

The study was conducted within Granger Basin (60°32′N, 135°18′W), a small headwater catchment of the Wolf Creek Research Basin, located approximately 15 km south of Whitehorse, Yukon (Fig. 1). The climate is subarctic continental, which is characterized by a large temperature range, low relative humidity, and low precipitation. Mean annual (1971–2000) temperature at the Whitehorse airport (706 m above sea level) is -0.7°C, with mean January and July temperatures of -17.7°C and +14.1°C, respectively, although winter and summer extremes of -40°C and 25°C are not uncommon. Mean annual precipitation is 267.4 mm, of which 145 mm falls as rain.

The drainage area of Granger Basin is approximately 7.6 km², and the elevation ranges from 1310 to 2250 m a.s.l. The lower half of the basin and most of the stream channel has a fairly gentle slope (~4°), however the upper portion of the basin is considerably steeper (~15-25°). Throughout the basin there are several small (~0.01 km²) ponds, and a permanent snowpack near the summit of Mount Granger.

Granger Basin lies within alpine and shrub-tundra ecological zones, with vegetation consisting predominantly of various willow (Salix spp.) and birch (Betula spp.) shrubs. A significant portion of the upper basin on the slopes of Mount Granger is covered with talus and bedrock outcrops. The lithology of the basin is predominantly sedimentary, comprising limestone, sandstone, shale, and conglomerate. A mantle of glacial till overlies most of the bedrock, ranging up to several meters in thickness. Fine-textured alluvium is found along much of the valley floor where the main channel resides, while colluvial deposits are more common along upper slopes away from the main valley. Soils are primarily orthic eutric brunisols with textures ranging from sandy loam to gravelly sandy loam. These are fairly well-drained soils with coarse parent materials. Surface organic soils range from 0.1 to 0.4 m in thickness, and are deepest in riparian areas and north-facing slopes throughout the basin, becoming thinner and more scattered in higher elevation and south-facing areas. Using the BTS method, it is estimated that approximately 70% of the basin is underlain with permafrost (Lewkowicz & Ednie 2004).

**Methodology**

**Field data**

Spring and summer discharge data were collected for Granger Creek over five years from 1999 to 2003 using an electronic stage recorder (Ott) placed inside a stilling well at the basin outlet. Measurements of stage were recorded at 15-minute intervals. A stage-discharge rating curve was developed by manual gauging of the stream at least 10 times per year. Rainfall data were collected using a Texas Instruments tipping bucket rain gauge, part of a nearby meteorology station (Fig. 1), measured rainfall depths in 0.1 mm increments and summed to the total number of these increments of each 30-minute period.

**Hydrograph analysis**

Hydrographs selected for analysis were taken after the snowmelt period (15 June) to eliminate diurnal fluctuations and mixed runoff signals. Visual inspection of the hydrographs was used to determine which events were suitable for analysis, and the selection criteria was based on distinct and isolated response events. In most cases, only storms >4 mm with one continuous or near continuous (<1 hour of no precipitation) event were chosen. In certain instances, additional precipitation following the peak in discharge prevented the determination of certain response factors. In these cases, the multiple input and flow peaks were treated as a single event to calculate runoff ratios and recession trends. Selected hydrographs were then isolated and analyzed separately.

The separation of stormflow runoff, \( R \), and baseflow components was carried out using a straight line drawn from the initial rise in flow to the point of greatest curvature on the recession limb (Fig. 2). The rational for this procedure was that previous research in permafrost environments had justified this method based upon the properties of permafrost soils (McNamara et al. 1998, Carey & Woo 2001b).

Hydrograph parameters were determined as shown in Figure 2. Input starts at time \( t_w^0 \) and ends at time \( t_w^e \), and total storm duration, \( T_w \), is given by, \( T_w = t_w^e - t_w^0 \). Total precipitation...
Figure 2. Hydrograph and precipitation parameters measured for analysis. Terms are provided in the text below.

is $P_i$. Stream response begins at time $t_{qc}$ and ends at time $t_{qc}^*$, peaking at time $t_{pk}$. The time duration of the storm hydrograph is $T_h = t_{qc}^* - t_{qc}$. The time of rise specifies the period of increasing discharge, or rising limb, and is determined as: $T_r = t_{pk} - t_{qc}$. Time of concentration, $T_c$, defined as the time required for the water to travel from the most hydraulically distant part of the contributing area to the basin outlet is: $T_c = t_{qc}^* - t_{we}$. The time between the beginning of input and the initial hydrograph response, known as the response lag is: $T_{LR} = t_{qc}^* - t_{we}$. Initial abstraction, $P_{abst}$, is as precipitation that falls prior to the initial rise in the storm hydrograph. The lag to peak discharge, $T_{LP}$, measures the time between the beginning of input and the hydrograph peak: $T_{LP} = t_{pk} - t_{0}$. The center of mass, or centroid, of both input and runoff is useful in characterizing time lags. In determining the center of mass, or centroid, for the input hydrograph, $t_{wi}$, the input values, $W_i$, measured for $i = 1, 2, n$ time periods of equal length as:

$$t_{we} = \frac{\sum_{i=1}^{n} W_i t_i}{\sum_{i=1}^{n} W_i}$$  \hspace{1cm} (1)$$

The centroid of the response hydrograph, $t_{qc}$, is determined in the same fashion, summing the event-discharge-weighted time values for equal length periods, and dividing by the sum of the event discharge values for each period:

$$t_{qc} = \frac{\sum_{i=1}^{n} Q_i t_i}{\sum_{i=1}^{n} Q_i}$$  \hspace{1cm} (2)$$

The centroid lag is defined as the period of time between the respective center of mass of the input and runoff events: $T_{LC} = t_{qc}^* - t_{we}$. The centroid lag to peak is the interval from the input center of mass to the peak discharge: $T_{LPC} = t_{pk} - t_{we}$.

Hydrograph recessions were analyzed for all of the selected stormflow events. The recession curve conveys information about watershed characteristics and storage properties, as it represents the natural storage that feeds the stream after the input has ceased. Numerous studies have focused attention on this part of the hydrograph, and many models have been develop to describe the decline in streamflow because of the importance in certain areas of hydrological application, including forecasting and water resource planning (see Tallaksen 1995 for review). Additionally, recession analysis has been used widely in permafrost environments (Dingman 1973, McNamara et al. 1998, Carey & Woo 2001b).

The most basic model for describing the recession is the linear-reservoir model of response, where water storage recharge and evaporation are neglected, given as:

$$q = q_s e^{(-t^*/a)}$$  \hspace{1cm} (3)$$

where $q$ is discharge, $q_s$ is the discharge at $t = 0$ (the beginning of the recession), $t$ is time, and $t^*$ is the recession parameter, also known as the turnover time, that describes the decay for the draining aquifer. The linear-reservoir model of watershed response has the advantage that it is simple and that $t^*$ is a widely used parameter for inferring watershed characteristics. However, this model is recognized as being valid over a limited range of the recession period (Tallaksen 1995).

**Results**

Post-freshet hydrographs (15 July to 15 September) are shown above in Figure 3. The interruption in the hydrographs in August 2003 was due to mechanical failure of the logger. Maximum annual flows occurred during snowmelt freshet (not shown) in May and early July when 30 to 50% of the annual precipitation was released over a several-week period. Following freshet, streamflow gradually declined throughout the summer and fall, with rainfall-runoff stormflow events superimposed on the seasonal recession. Discharge rates were typically below 0.4 m$^3$s$^{-1}$ following snowmelt, and gradually declined to ~0.05 m$^3$s$^{-1}$ before stream gauging ceased prior to freezing. The 2000 hydrograph shows greater flows than other years, with baseflow rates of ~0.25 m$^3$s$^{-1}$ in early summer, which later rose to 0.3 m$^3$s$^{-1}$ triggered by a series of storms in late August. By late September 2000, the flow rate had fallen to ~0.2 m$^3$s$^{-1}$.

Rainfall from 15 June to 15 September over the five years was 141, 234, 141, 130, and 129 mm for 1999 to 2003, respectively. In 1999, 2001, and 2002, ~8 rainfall events following the snowmelt period were >4 mm in magnitude, whereas 2000 and 2003 were wetter with 15 and 13 events >4 mm, respectively. The average rainfall for all storms (including those not analyzed) over all years was 8.1 mm with a maximum of 31.8 mm. Rainfall intensities varied from 0.2–2.6 mm hr$^{-1}$, averaging 0.8 mm hr$^{-1}$. Storms selected for analysis ranged between 2 and 48 hours with an average of 6 hours.

**Hydrograph timing response**

During the 5-year study period, 49 rainfall-runoff stormflow events passed the selection criteria and were analyzed for response lags and time durations. A summary of the hydrograph parameters is presented in Table 1. A Spearman rank (Sr) correlation coefficient matrix ($p < 0.05$) of all measured variables was performed to explore relations among hydrograph parameters, rainfall and date (Table 2). Response lags ($T_{R,s}$) ranged between 0 and 11.2 hours, with an average time of 2.4 hours. McNamara et al. (1998) reported a mean response time of 2.15 hours (range 0–6
hours) for Imnavait Creek, a continuous permafrost basin (2.2 km$^2$) in northern Alaska. Compared with temperate basins, the average response time was rapid, and the results are consistent with Church (1974) who also reported that rapid response times are a characteristic of northern rivers.

Initial abstractions ($P_{\text{abst}}$) were low, ranging from 0 to 4.1 mm with an average of 1.1 mm. An unexpected significant positive relation existed between $P_{\text{abst}}$ and antecedent discharge, ($Q_{\text{ant}}$) ($Sr = 0.32$), indicating that more water was abstracted when the catchment was wettest. On the other hand, watershed wetness as represented 5-day antecedent rainfall ($P_{\text{5day}}$) showed no relation with $P_{\text{abst}}$. A lack of correlation between $P_{\text{abst}}$ and wetness indices has been reported previously for subarctic and arctic watersheds (Dingman 1973, McNamara et al. 1998, Carey & Woo 2001b), and is typically attributed to limited subsurface storage capacity due to the presence of permafrost.

The time of rise ($T_w$) for most hydrographs was similar to the duration of precipitation ($T_p$). The lag to peak ($T_{ip}$), centroid lag to peak ($T_{ipc}$), and centroid lag ($T_{ic}$) were short, with averages of 11.8, 5.8, and 8.1 hr, respectively. This is in contrast to values of $T_{ip}$ and $T_{ic}$ of 17.8 and 34.8 hr for Imnavait Creek reported by McNamara et al. (1998). The centroid lag for Granger Basin was closer to the average of 19.5 hr reported by Holtan & Overton (1953) in a study of 40 streams in the conterminous United States, ranging from 76 km$^2$ to 3200 km$^2$ in basins that are much larger than the study catchment. Both $T_{ip}$ and $T_{ic}$ were positively correlated ($Sr = 0.31$ and 0.29, respectively) with $Q_{\text{ant}}$.

Runoff ratios ($R/P$) were highly variable, ranging between 0 and 0.33, with an average of 0.1. These values were low when compared with studies from other permafrost basins and hill slopes (Dingman 1971, Slaughter et al. 1983, Woo 1983, McNamara et al. 1998, Carey & Woo 2001b). Seasonally, higher runoff ratios were associated with early periods following melt when the frost and water table was near the surface, and ratios progressively diminished as summer progressed and the active layer thickened (Fig. 4a). A strong negative relationship existed between runoff ratio and Julian Day ($Sr = -0.74$). Runoff ratio increased with $Q_{\text{ant}}$ ($Sr = 0.55$), yet there was no significant relation between runoff ratio and $P_{\text{5day}}$. Additionally, there was no relation between runoff ratio and total rainfall and rainfall intensity.

**Streamflow recessions**

Hydrograph recessions were observed to be temporally variable, with steeper recession limbs characteristic of earlier season discharge events that flattened out as summer progressed (Fig. 4b). Values of the $t^*$ parameter ranged between 7.7 and 163.1 hr with an average of 41.7 hr, which compared well with other permafrost and organic-covered permafrost basins of similar area. For example, Dingman (1971) reported an average $t^*$ of 39 hours for Glenn Creek, Alaska, while McNamara et al. (1998) found this value to be 30.2 hours for Imnavait Creek. There was a strong positive relationship between $t^*$ and Julian Day ($Sr = 0.69$) indicating that as the season progresses and soils thaw, runoff reached the stream through deeper, less conductive soils. As would be expected, $t^*$ increased with decreasing runoff ratio ($Sr = \ldots$)

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Table 1. Summary of hydrograph parameters for 49 storms. Terms are defined in text.

<table>
<thead>
<tr>
<th>Hydrograph Parameter</th>
<th>Mean</th>
<th>Standard Deviation</th>
<th>Maximum</th>
<th>Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>$R/P$</td>
<td>0.09</td>
<td>0.09</td>
<td>0.33</td>
<td>0.00</td>
</tr>
<tr>
<td>$t^*$ (h)</td>
<td>41.70</td>
<td>32.20</td>
<td>163.10</td>
<td>7.70</td>
</tr>
<tr>
<td>$P_{\text{int}}$ (mm)</td>
<td>0.79</td>
<td>0.84</td>
<td>5.20</td>
<td>0.18</td>
</tr>
<tr>
<td>$P_{\text{abst}}$ (mm)</td>
<td>1.05</td>
<td>0.96</td>
<td>4.10</td>
<td>0.00</td>
</tr>
<tr>
<td>$P_{\text{5day}}$ (mm)</td>
<td>7.72</td>
<td>6.81</td>
<td>29.30</td>
<td>0.00</td>
</tr>
<tr>
<td>$T_w$ (h)</td>
<td>12.19</td>
<td>8.70</td>
<td>46.00</td>
<td>0.50</td>
</tr>
<tr>
<td>$T_{ip}$ (h)</td>
<td>2.44</td>
<td>2.72</td>
<td>11.25</td>
<td>0.00</td>
</tr>
<tr>
<td>$T_{ipc}$ (h)</td>
<td>9.56</td>
<td>6.52</td>
<td>33.50</td>
<td>2.00</td>
</tr>
<tr>
<td>$T_{ic}$ (h)</td>
<td>11.83</td>
<td>6.47</td>
<td>34.75</td>
<td>3.50</td>
</tr>
<tr>
<td>$T_{ipc}$ (h)</td>
<td>5.80</td>
<td>3.38</td>
<td>18.75</td>
<td>0.36</td>
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<tr>
<td>$T_{ic}$ (h)</td>
<td>8.07</td>
<td>3.15</td>
<td>16.10</td>
<td>1.37</td>
</tr>
<tr>
<td>$T_i$ (h)</td>
<td>25.21</td>
<td>13.81</td>
<td>72.50</td>
<td>6.50</td>
</tr>
<tr>
<td>$T_{ip}$ (h)</td>
<td>15.29</td>
<td>7.97</td>
<td>45.50</td>
<td>4.00</td>
</tr>
</tbody>
</table>

Figure 3. Post-freshet hydrographs (15 June–15 September) for Granger Basin, 1999–2003.
Table 2. Spearman rank correlation matrix. Values in bold are significant at the 95% confidence level. Terms defined in text.

<table>
<thead>
<tr>
<th>Julian Day</th>
<th>$P_t$</th>
<th>$Q_{ant}$</th>
<th>$R/P_t$</th>
<th>$t^*$</th>
<th>$P_{ant}$</th>
<th>$P_{abst}$</th>
<th>$P_{5d}$</th>
<th>$T_w$</th>
<th>$T_{LR}$</th>
<th>$T_r$</th>
<th>$T_{LP}$</th>
<th>$T_{LPC}$</th>
<th>$T_c$</th>
<th>$T_b$</th>
<th>$T_c$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Julian Day</td>
<td>1.00</td>
<td>-0.35</td>
<td>0.69</td>
<td>-0.74</td>
<td>0.23</td>
<td>0.03</td>
<td>0.23</td>
<td>0.24</td>
<td>-0.12</td>
<td>-0.12</td>
<td>-0.25</td>
<td>-0.04</td>
<td>-0.01</td>
<td>-0.24</td>
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<tr>
<td>$P_t$</td>
<td>1.00</td>
<td>-0.10</td>
<td>0.55</td>
<td>0.11</td>
<td>0.13</td>
<td>0.32</td>
<td>0.45</td>
<td>0.19</td>
<td>0.17</td>
<td>0.31</td>
<td>0.23</td>
<td>0.29</td>
<td>0.20</td>
<td>0.17</td>
<td></td>
</tr>
<tr>
<td>$Q_{ant}$</td>
<td>1.00</td>
<td>-0.66</td>
<td>-0.07</td>
<td>-0.25</td>
<td>0.07</td>
<td>0.10</td>
<td>0.26</td>
<td>0.15</td>
<td>0.04</td>
<td>0.08</td>
<td>-0.11</td>
<td>0.12</td>
<td>0.06</td>
<td>-0.17</td>
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<tr>
<td>$R/P_t$</td>
<td>1.00</td>
<td>0.04</td>
<td>-0.02</td>
<td>-0.04</td>
<td>0.01</td>
<td>-0.13</td>
<td>0.26</td>
<td>0.20</td>
<td>0.25</td>
<td>0.24</td>
<td>0.31</td>
<td>0.47</td>
<td>0.31</td>
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<td></td>
</tr>
<tr>
<td>$t^*$</td>
<td>1.00</td>
<td>0.29</td>
<td>0.30</td>
<td>0.02</td>
<td>0.61</td>
<td>0.24</td>
<td>0.46</td>
<td>0.44</td>
<td>0.04</td>
<td>0.24</td>
<td>0.53</td>
<td>0.23</td>
<td>0.07</td>
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<td></td>
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<tr>
<td>$P_{5d}$</td>
<td>1.00</td>
<td>-0.21</td>
<td>0.12</td>
<td>-0.44</td>
<td>-0.26</td>
<td>-0.23</td>
<td>-0.46</td>
<td>-0.43</td>
<td>-0.50</td>
<td>-0.29</td>
<td>0.14</td>
<td>0.07</td>
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<tr>
<td>$T_w$</td>
<td>1.00</td>
<td>0.10</td>
<td>0.50</td>
<td>0.68</td>
<td>-0.11</td>
<td>0.21</td>
<td>0.02</td>
<td>0.27</td>
<td>0.08</td>
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<tr>
<td>$T_{LR}$</td>
<td>1.00</td>
<td>-0.04</td>
<td>0.17</td>
<td>-0.08</td>
<td>-0.03</td>
<td>0.08</td>
<td>0.08</td>
<td>0.03</td>
<td>-0.06</td>
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<tr>
<td>$T_r$</td>
<td>1.00</td>
<td>0.43</td>
<td>0.59</td>
<td>0.78</td>
<td>0.35</td>
<td>0.57</td>
<td>0.66</td>
<td>0.23</td>
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<tr>
<td>$T_{LP}$</td>
<td>1.00</td>
<td>-0.18</td>
<td>0.34</td>
<td>0.04</td>
<td>0.14</td>
<td>-0.09</td>
<td>-0.12</td>
<td>0.53</td>
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<tr>
<td>$T_{LPC}$</td>
<td>1.00</td>
<td>0.78</td>
<td>0.64</td>
<td>0.63</td>
<td>0.88</td>
<td>0.53</td>
<td>1.00</td>
<td>0.76</td>
<td></td>
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<tr>
<td>$T_c$</td>
<td>1.00</td>
<td>0.69</td>
<td>0.68</td>
<td>0.67</td>
<td>0.41</td>
<td>0.33</td>
<td>1.00</td>
<td>0.76</td>
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<tr>
<td>$T_b$</td>
<td>1.00</td>
<td>0.60</td>
<td>0.41</td>
<td>0.33</td>
<td>1.00</td>
<td>0.76</td>
<td>1.00</td>
<td></td>
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</table>

-0.66). Recession constants were compared with total rainfall ($P_t$), antecedent wetness indices ($Q_{ant}$, $P_{5d}$), and other storm characteristics to assess for any influence of input volume, intensity, or watershed wetness, yet these relations were poorly defined and not statistically significant at the 95% confidence level.

**Discussion and Conclusion**

Simple analysis of stormflow hydrographs provide useful insight into the dynamics of runoff generation as permafrost-underlain catchments, unlike more temperate catchments, undergo significant physical changes throughout the summer due to ground thaw. For example, the decline in runoff ratio implies a widespread increase in soil storage capacity as the active layer deepens, the water table descends atop the frost table, and rainfall is able to percolate into deeper, less permeable, mineral soils. The hydraulic conductivity of mineral soils is typically orders of magnitude less than organic soils (Carey & Woo 2001b), resulting in increased transmission times to the stream and larger $t^*$.

Figure 4. Seasonal progression of (a) runoff ratio ($R/P_t$), and (b) recession parameter, $t^*$, for 49 stormflow events between 1999 and 2003.

$t^*$ indicates water inputs take progressively longer to reach the stream due the gradual deepening of the flow pathways into less transmissive soil layers. Results from Granger Basin compare well with others reported in permafrost regions (Dingman 1973, Slaughter et al. 1983, McNamara et al. 1998) and support conceptual models of runoff generation being controlled by the relation between frost and water table positions for this environment (Carey & Woo 2001b).

Hydrograph lag-time indices had little correspondence with time of year or wetness, implying at the basin scale, these variables were not controlled explicitly by permafrost-related processes, but rather to other catchment characteristics (which may be affected by the presence of permafrost). The lack of correlation between response lags ($T_{LR}$), initial abstractions ($P_{abst}$), and measures of basin wetness such as antecedent discharge ($Q_{ant}$) and 5-day rainfall ($P_{5d}$) indicate that certain areas of the basin (footslopes of permafrost-underlain slopes and riparian areas) remain wet, contributing water rapidly to the stream after rainfall begins. The spatial extent of these wet areas expands and contracts away from the stream based on time of year and basin wetness, which is reflected by the declining trend in runoff ratios ($R/P_t$) throughout the summer. This process is similar to that reported by Quinton & Marsh (1998) and Carey & Woo (2001b), whereby hill slopes become effectively disconnected from the stream as the season progresses.

The recession coefficient, $t^*$, was strongly related to time of year and runoff ratio, yet had no relationship with precipitation characteristics. Shallow thaw depths in the early summer lead to rapid drainage of the slopes through near-surface organic soils and preferential pathways that are well-linked. As the active layer deepens, the water table descends atop the frost table, and rainfall is able to percolate into deeper, less permeable, mineral soils. The hydraulic conductivity of mineral soils is typically orders of magnitude less than organic soils (Carey & Woo 2001b), resulting in increased transmission times to the stream and larger $t^*$. 
Hydrograph parameters investigated in Granger Basin, a discontinuous permafrost alpine basin, indicate that at the headwater scale, streamflow response reflects the influence of permafrost throughout the post-freshet season. Hydrological models that use these parameters in calibration must consider their temporal dependent nature.

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References


