A Shifting Hydrological Regime: A Field Investigation of Snowmelt Runoff Processes and Their Connection to Summer Baseflow, Sunshine Coast, B.C.

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ABSTRACT

The annual hydrographs of British Columbian rivers are either characterized by glacial, nival, pluvial or "hybrid" (both pluvial and nival) sources of runoff. Climate change scenarios for the 2050s indicate that snow-water-equivalent (SWE) could diminish by 50 to 80% in lower snowfed-dominated basins in the South Coastal region of B.C. compared to historical values. This could trigger a shift from a hybrid to a pluvial regime for many creeks originating in the coastal mountains, including streams used as primary water supply such as Chapman Creek on the Sunshine Coast. It has been suggested in previous studies that this change in runoff regime will negatively impact summer low-flows due to an earlier onset of snowmelt and a prolonged summer recession period. However, the connection between groundwater recharge during snowmelt and late-summer water yield remains unclear. A local headwater catchment (Stephen's Creek) was instrumented and monitored from the fall of 2008 to the fall of 2009. A two- and a three-component isotopic hydrograph separation (2-, 3-IHS) method was developed by adapting the runoff-corrected model (runCE) to a semi-distributed environment in order to account for spatial variability in snowmelt and in isotopic release from the snowpack. IHSs results show that event water (snowmelt) and soil water composed most of the streamflow both at the headwater site (66 ± 19%) and at the mouth (62 ± 23%) during the peak of the freshet, while the contribution of event water to streamflow was significantly different in July (34 ± 11 % at the headwater site vs. 7 ± 4% at the mouth). Hydrometric, isotopic and geochemical data suggest that saturated throughflow was the predominant flow-path taken by melt water during freshet. Preliminary streamflow recession analysis revealed that the snowmelt-recharged headwater catchment can support a steadier summer baseflow than Robert's Creek—a much larger, but rainfed-dominated watershed. It is concluded that the large input of melt water during the spring was sufficient to "over-turn" the shallow subsurface reservoir of the headwater catchment and recharge deeper flow-paths at a rate that can not be matched by rainfed-dominated systems. The results are of interest to water resource planning in the South Coastal region.

Keywords: hydrograph separation, recession analysis, temperature-index model, hydrological regime, snowmelt, low-flows, climate change, British Columbia

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INTRODUCTION

Climate change has emerged as a priority for water resource managers from the Western U.S. to Southern British Columbia (Snover *et al.*, 2003; Markoff and Cullen, 2007). In these regions, autumnal rainfalls and spring freshet from headwater catchments largely dominate the hydrograph of streams that are not fed by glacial melt. These systems, when driven by these two major hydrological responses, are known as "hybrids" (Eaton and Moore, 2010). Mounting evidences derived from historic trends and climate models for the Pacific Northwest's coastal region suggest that these streams will eventually shift to a pluvial-only regime within upcoming decades. As a result, the onset of summer low-flows will likely occur earlier (Rodenhuis *et al.*, 2007). However, it is yet unclear as to what magnitude the discharges will be affected by this shift in hydrological regime. In coastal systems, summer low-flows have mainly decreased in hybrid systems (Whitfield, 2001; reported by Moore *et al.*, 2007). This has been interpreted by Whitfield as being the result of an earlier onset of snowmelt and an extended streamflow recession period in the summer. This interpretation was challenged by Moore *et al.* (2007), who found that the controlling factor explaining the decrease in September streamflow is primarily the decrease in September precipitation, as opposed to lagged variables such as winter precipitation.

Field-based studies that specifically investigate snowmelt flow-paths and the transition from freshet conditions to late summer baseflow are still greatly needed, especially in coastal areas. At the "runoff processes" scale in unsaturated environments, not much evidence in the literature suggests that snowmelt events recharge aquifers differently than rainfall events. Krabbenhoft *et al.* (1990) estimated groundwater – surface water interactions in a Wisconsin's lake-dominated system over a two-year monitoring period. The authors found a significant difference between the $\delta^{18}O$ signatures of total precipitation and groundwater (−0.6‰), which was attributed to the "selective" recharge of spring snowmelt.

The aim of this field-oriented study was to determine whether or not the shift from a hybrid to a pluvial hydrological regime, caused by climate change, has the potential to negatively impact late summer water yield in BC's coastal environment. Two research objectives were developed around these specifics: (1) Investigate melt-water runoff mechanism and flow-path by performing a two- and a three-component isotopic hydrograph separations (IHS) during spring freshet, and into the summer low-flow period; and (2) Compare the streamflow recession behaviour of a snowfed headwater catchment and an adjacent rainfed watershed by using existing recession models. Here, we present a semi-distributed modelling scheme that empirically accounts for spatial and temporal variability in snowmelt and in isotopic release from the snowpack by pairing the YAM temperature-index model (Jost *et al.*, submitted) with the runCE triangular-weighting IHS method (Laudon *et al.*, 2002).

STUDY SITE

The study site includes two adjacent watersheds, Stephen's Creek (2.4 km^2) and Roberts Creek (30.2 km^2), located in B.C.'s Sunshine Coast (Canada), 25 km northwest of Vancouver (Figure 1). The research catchment is located in the headwater of Stephen's Creek and comprises 718 ha ranging in elevation from 670 m at the catchment outlet to 1,170 m at the most eastern divide point. The catchment has a pronounced snowmelt component due to the convex geomorphology of the upper drainage, where about 70% of the catchment area lays above 1000 m. Roberts Creek's hydrograph is more typical of a rain-fed watershed due to the different geomorphology of the drainage area (Figure 1b).

A Mediterranean-like climate dominates over this part of British Columbia. The bedrock is from a metavolcanic orogenesis and is overlaid by a highly compacted sub-glacial till. The dominant soil type is Ferro-Humic Podzol with a thickness of ~130 cm close to the catchment outlet and ~70 cm close to the divide based on observations made at 4 soil pits. Cemented Fe_2O_3-enriched pans with hydraulic characteristics similar to sub-glacial till were observed at the C-horizon contact zone (1.3 m to 0.95 m deep) for the 3 soil pits at lower elevation. The research catchment is located in the transitional area from the Coastal Western Hemlock (CWH) to the Mountain Hemlock (MH) biogeoclimatic ecosystem subzones. The forest cover of the catchment is highly heterogeneous in age and structure due to past forest harvesting.

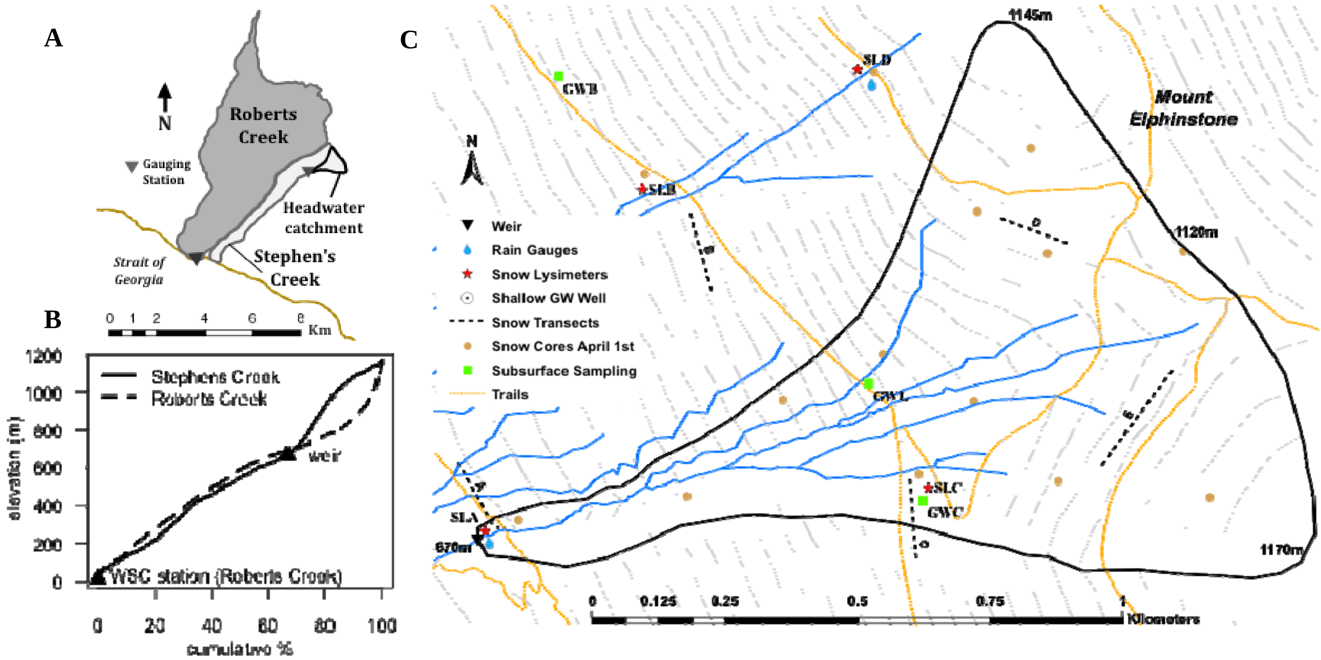

Figure 1. (a) Localization of the research area, (b) hypsometric curves of Roberts Creek and Stephen's Creek watersheds, and (c) instrumentation of the catchment area, Stephen's Creek headwater

FIELD METHOD AND LABORATORY ANALYSIS

The research catchment has been equipped with a sharp-crested 100° V-notch weir at the outlet. Water-level was recorded using a capacitance water-level probe and stream discharge was computed by developing a rating curve using salt-tracing flow measurements (slug injections) as per the method described by Moore (2005). Shallow groundwater-level was monitored in a sand-filled depression (vernal pool) located at the base of a hillslope close to the outlet of the catchment and 15 m away from the stream channel. Rainfall intensity was recorded at the outlet of the catchment (RGW) and close to the divide (RGE) using tipping buckets rain gauges. Total precipitation for the winter months were derived from Gibsons Gower Point weather station (# 1043152, Environment Canada, 2010) using a static linear elevation lapse rate. Air temperature was monitored hourly at mid-elevation (975 m) in the catchment. In order to account for isotopic fractionation processes driven by snowmelt, the use of four 6 m^2 snowmelt (pan) lysimeters was preferred to characterise the isotopic signature of event water (Moore, 1989; Laudon *et al.*, 2002). The instruments were installed under a forest cover representative of their elevation band. Snowpack drainage water was sampled daily in the afternoon from April 4th until the snowpack was completely melted. Four 150 m snow transects were sampled weekly at different elevation for snow depth and snow density using the standard method detailed by Goodison *et al.* (1981). Fifteen snow wires were used for the fifth transect on the northwest facing aspect of the catchment at higher elevation (1090 m) due to the extensive depth of the April 1st snowpack. Although the snow wire technique is usually used to calculate daily ablation rate (Mielko and Woo, 2006), it is also an effective mean to measure snow depth where the usual probe fails to reach the ground. A single snow-density measurement was conducted in undisturbed areas within a meter of each snow wire. Stream water was sampled daily to weekly at two different locations along Stephen's Creek: at the outlet of the catchment (STH – 670 m) and at the mouth (STM – 26 m). Saturated soil water through-flow was collected intermittently from three soil profiles (GWC, GWB, GWL) during the period extending from April 25th to June 14th. Fifteen depth-integrated snowpack samples were taken on March 31st across the catchment and melted using the method detailed by Cooper (1998) to determine the initial isotopic and chemical signatures of the snowpack prior to snowmelt.

METHOD: SEMI-DISTRIBUTED HYDROGRAPH SEPARATION MODELS

The present study attempts a two-component isotopic hydrograph separation (2-IHS), separating the input of "new" water (i.e., snowmelt) in the stream from the "old" water previously stored in the catchment,

$$Q_sC_s = Q_eC_e + Q_pC_p \qquad (1)$$

where Q stands for flux of water, C for isotopic concentration and the subscripts s, e and p for streamflow, event and prevent components respectively. The data required to partition the hydrograph into two components seem minimal, but IHS techniques involve a number of assumptions that can be fairly difficult to meet (reviewed by Buttle, 1998). Amongst them, the isotopic signature of event water is assumed to be constant in time and space. To the best of the authors' knowledge, no published IHS studies have reported statistically significant spatial heterogeneities in the snowmelt isotopic signal. For instance, Moore (1989) failed to reject the null hypothesis stating that no significant differences exist between the outflow concentration from eight snow lysimeters at a 95% level of confidence (p = 0.057 for D and p = 0.595 for ^{18}O). Furthermore, evidence presented by Laudon (2007) also supports a spatially uniform snowpack from a study conducted in a 67km^2 basin in Sweden where the standard deviation for δ^{18}O was only 0.4‰ (n= 40 snowcores). However, it is clear that spatial heterogeneities in the isotopic signature of snowmelt can commonly be encountered in mountainous landscapes due, amongst other things, to fractionation processes driven by elevation and to the variability of the freezing-level. Whyte (2004 – unpublished) attempted a two-component hydrograph separation during snowmelt in B.C.'s Slocan valley, but the author was unsuccessful to characterize the event water isotopic signature due to spatial variability—consequently the results could not be quantified. The present study was able to account for the spatial and temporal variations in snowmelt output and in isotopic signature by combining the snow-water-equivalent (SWE) routine of the YAM temperature-index snowmelt model (Jost *et al.*, submitted) to the runCE triangular-weighting transfer function (Laudon, 2002).

The headwater catchment was subdivided into 22 cells based on elevation, forest structure, aspect and slope. Since the precipitation data for the catchment were judged unreliable during the winter, the YAM simulation was conducted by giving an initial SWE value to each cell. Those values were linearly interpolated using elevation as a predictor based on the March 30th measurements at the snow transects. The model was calibrated to daily increments using snow course measurements. In addition, an initial cold content value was given to higher elevation cells by calibrating the SWE balance to the drainage outflow from the snow lysimeters (SLs). The daily snowpack drainage output for each cell was computed by adding the throughfall values lapsed for elevation to the negative rate of change in SWE modelled by YAM. This approach assumes a saturated snowpack, which is a fair assumption during the spring in BC's south-coastal environment at mid-elevation.

Spatial and temporal trend in the isotopic signature were tested through a multiple linear regression (MLR) and through a two-way analysis of variance (ANOVA) by treating time and elevation as factors, as proposed by Moore (1989). The time-series was divided into two periods: early and late spring. The two-way ANOVA revealed that both elevation and time were significantly related to δ^{18}O variations for the whole snowmelt season ($p < 0.001$). The MLR confirmed a fractionation trend based on elevation for the whole season ($p < 0.008$), while the enrichment trend could only be validated for early spring ($p < 0.001$) as opposed to late spring ($p > 0.32$).

These results suggest that the spatial variance observed in the snowpack drainage-output during the ablation season can be well explained by the altitudinal fractionation of winter precipitation. The $\delta^{18}O$ signature of each grid cell was modelled with the SLs time series through daily linear regressions using mean elevation as a predictor. The predicted values were discarded and replaced by a daily average when the coefficient of determination (R^2) was less than 0.75. A mass balance approach was used to determine if the depth-integrated snow core samples taken on March 31st varied spatially in accordance with the simulated depth-integrated snowmelt isotopic values. The daily isotopic signature was converted to a flux by multiplying it by the daily ΔSWE modelled by YAM:

$$\text{Mass Balance}_j = \frac{\left(\sum_{i=1}^{t} M_{j(i)} \cdot \delta^{18}O_{j(i)}\right) - \left(SWE_{j(1)} \cdot \delta^{18}O_{j(sc)}\right)}{\left(SWE_{j(1)} \cdot \delta^{18}O_{j(sc)}\right)} \cdot 100 \qquad (2)$$

where the mass balance for the j^{th} cell is given as a percentage, where M is the daily ΔSWE given by YAM, where $SWE_{j(1)}$ is the initial SWE value as modelled by YAM and where the subscript *sc* refers to snow core values. Rainfall precipitation was left out of the term M since it cannot be accounted for by the initial snowpack sampling. A preliminary assessment at the SLs allowed defining the natural "imbalance" of the open system by evaluating the uncertainty created by the spatial regression models. This calculation was subsequently applied to the results obtained from the regression models and the closing errors of the cells (−7.3 to 2.7% at 70% level of confidence) were comparable to the ones obtained at the SLs (−4.2 to 1.2% at 70% LoC).

The time lag for the event water to reach the channel was accounted for by the runoff corrected model (runCE – Laudon *et al.,* 2002), which computes the event water signature by correcting for the weighted isotopic signature of the cumulative amount of snowmelt (depth) that has left the snowpack at time *t* but has not yet been discharged to the stream. The runCE triangular weighting function (eq. 3) was applied to each cell,

$$\delta^{18}O_{e(t)} = \frac{\left(\sum_{i=1}^{t} M_{(i)} \cdot \delta^{18}O_{m(i)} - \sum_{i=1}^{t} E_{(i)} \cdot \delta^{18}O_{e(i)}\right)}{\left(\sum_{i=1}^{t} M_{(i)} - \sum_{i=1}^{t} E_{(i)}\right)} \qquad (3)$$

where $M_{(i)}$ is the incrementally collected melt and rain water depth, $E_{(i)}$ is the incrementally calculated event water discharged to the stream and where the subscripts *e* and *m* stands for event and melt water respectively. The value for $E_{(i)}$ is determined from the fraction of event water in the stream (derived from eq. 1). For details on the runCE model consult Laudon (2002). The daily event water signatures for all cells were subsequently weighted by area and averaged to obtain an "integrated" event water time series for the whole catchment. For this study, the commonly used first order propagation of uncertainty adapted by Genereux (1998) for 2-IHS models and applied by Laudon (2002) with the runCE model was chosen to compute uncertainty. The analytical uncertainty (0.1‰) was propagated for streamwater and pre-event water, while the unexplained variance for elevation gain as expressed by the averaged residual standard errors for the daily regressions (0.44‰) was propagated for event water. A water-balance was attempted by simulating evapotranspiration using the Shuttleworth-Wallace method built-in as a subroutine in the lumped Brook90 hydrologic model version 4.4 (Federer, 2003) as proposed in McHale *et al.* (2002).

RESULTS

Snowmelt Runoff Mechanism

The daily water-levels at the piezometer location showed a marked counter clock-wise hysteresis loops when plotted against daily stream discharge from the catchment (Figure 2). Also, strong diel fluctuations were observed in stream discharge but not in shallow groundwater levels (Figure 3). These characteristics indicate that the piezometer in the research catchment was monitoring a perched water table fed by hillslope contributions. Field observations done during snowmelt by Kendall *et al.* (1999) found that these counter clock-wise hysteresis patterns are typical of hillsopes (i.e. recharge zone) while clock-wise patterns and strong diel fluctuations occur in the riparian zone (findings supported by Kim *et al.*, 2004). The pool sustained high water-levels long after the snow has melted in the vicinity of the instrument, as modelled by YAM (despite the fact that it was installed in a highly conductive deposit), before pore-water suddenly drained at the end of May—probably due to an abrupt cessation of hillslopes hydrologic connectivity (Figure 3). This piezometeric "collapse" occurred when the snowline reached 1100 m on the southeast facing aspect. Evapotranspiration increased by 122% between the last two weeks of May (May 18th to 24th: 0.36 ± 0.24 mm; May 25th to May 31st: 0.8 ± 0.45 mm) based on the Brook90 model. This increase is significant but small in absolute terms and is not likely to explain on its own the fast water-level drop observed at the piezometer.

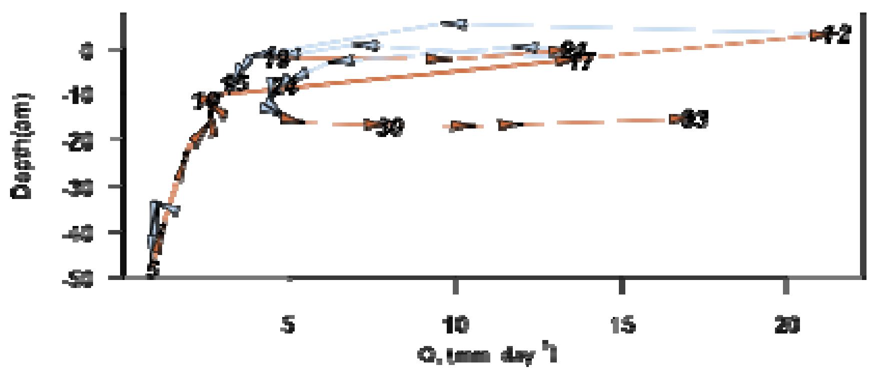

Figure 2. Stephen's Creek discharge at the weir plotted against shallow groundwater-level from April 1st to May 3rd 2009 (day 1 to 33, some are numbered). The rising limb is coloured brown and the falling limb is light blue.

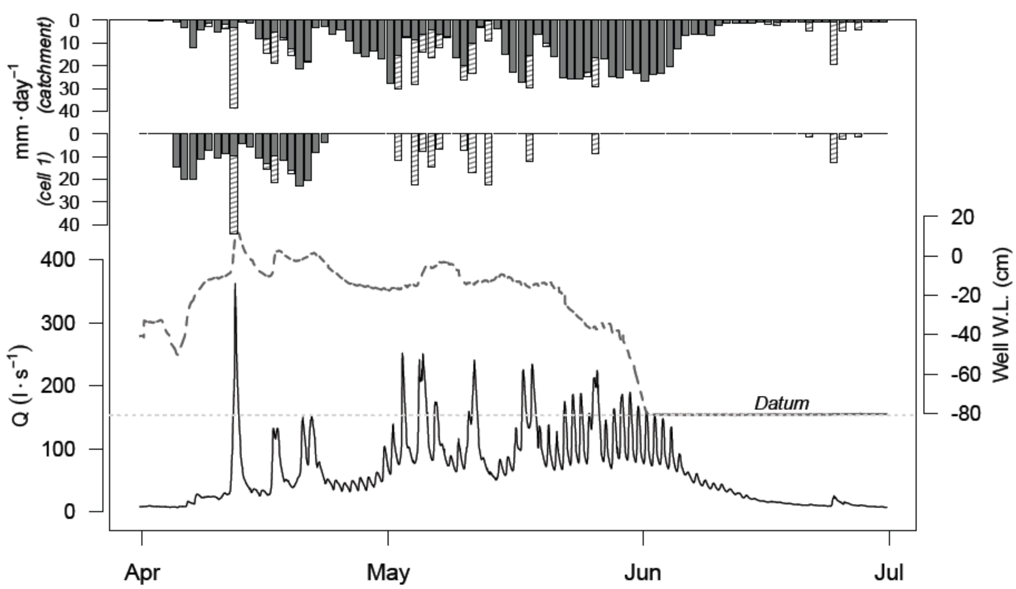

Figure 3. Instantaneous discharges for Stephen's Creek at the weir (solid line), piezometer water-level fluctuations (dashed line). The upper bar plot represents the area-weighted average snowpack drainage-output for the whole catchment (solid bars are snowmelt as modelled by YAM and gradient bars are throughfall) while the lower bar plot shows the modelling-cell where the piezometer is located.

Hydrograph Separation

Two-component hydrograph separation results showed that pre-event water is dominating the hydrograph in April, representing in average 62 ± 11% of the streamflow (Figure 4). This is in accordance with most 2-IHS studies conducted during snowmelt (Moore, 1989, Rodhe, 1998; Laudon *et al.*, 2002-2004-2007). However, the contribution of event water drastically increases as the snowmelt season progresses into the month of May. The average event water contribution to streamflow from April 30th to June 5th is estimated to 78 ± 26%, then slowly decreases to 37 ± 10% for the remaining of June and down to 24 ± 8% in average for the month of July. Out of the 1106 mm of snowmelt/rainfall input to the catchment from April 1st to September 1st; water-balance figures estimated that 491 mm directly contributed to streamflow, 271 mm replaced the discharged pre-event water in subsurface storage, 197 mm evapo-transpired and 147 mm were net gain for the subsurface storage to be carried over into the winter. The total uncertainty of the 2-IHS separation is estimated to ± 121 mm.

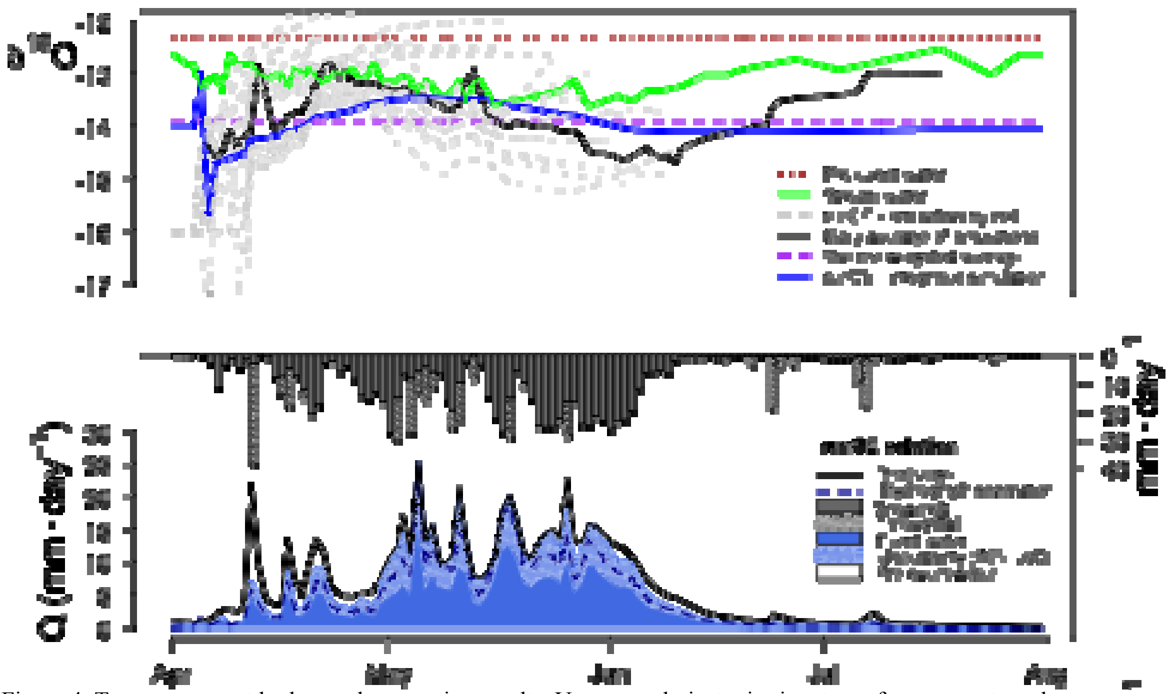

Figure 4. Two-component hydrograph separation results. Upper graph: isotopic signature of components and output from the runCE simulation (event water). Lower graph: hydrograph separation using the runCE method.

A two-component separation was also performed at the watershed scale (Table 1). The errors associated with rainfall contributions in the summer were minimized by sampling baseflow at least 72 hours after any rainfall event had occurred. The comparison between the headwater catchment and the whole watershed was done by characterizing the event water signature through the traditional volume-weighted average approach (Mast *et al.*, 1995) because mathematical convergence could not be achieved when applying runCE at Stephen's Creek at the mouth, likely due to an insufficient difference between pre-event water and runCE's event water isotopic signature. The contributions of event water were very similar at both scales during the freshet. However, during the month of July event water made-up 34 ± 11% of the streamflow in the catchment as opposed to only 7 ± 4% at the mouth. Only 30 mm of un-accounted rainfall occurred in early July, which is likely not sufficient to bias these estimates.

Table 1 Summary of event water contribution (%) to the streamflow for Stephen's Creek at the weir (headwater catchment) and Stephen's Creek at the mouth based on two 2-IHS methods

Period	**runCE**	**Volume-weighted average (VWA)**		
	Headwater catchment (%)	Headwater catchment (%)	Stephen's Creek watershed (%)	Paired Student's *t* test (p-value)
April 1st to April 29th	37 ± 11	41 ± 12	34 ± 12	0.013
April 30th to June 5th	78 ± 26	66 ± 19	62 ± 23	0.044
June 6th to June 30th	38 ± 10	43 ± 13	41 ± 15	0.407
July 1st to July 31st	24 ± 8	34 ± 11	7 ± 4	**<0.001**

A three-component hydrograph separation (3-IHS) method was performed as proposed by Hinton *et al.* (1994) to partition streamflow based on geographical sources of runoff using silicon as a secondary tracer (Figure 5). Soil-water isotopic concentration was characterized with biweekly samples from the saturated throughflow resurgence points in the research area, while soil-water silicon concentrations had to be defined based on literature values for similar forested ecosystems (3.53 ± 0.65 ppm; reported by Cornelis *et al.*, 2010 for Douglas fir forests at 15 cm depth) because the large scatter observed in the measured concentrations (1.82 ± 0.8 ppm, $n = 17$) during snowmelt is not assumed to be representative of pre-event concentrations. Therefore, the interpretation of the 3-IHS results should be done with supplementary caution.

The results show little groundwater contribution to streamflow during the bulk of the freshet. The dominating groundwater contribution during the April 12th rain-on-snow event and its decreasing influence thereafter seems to be in accordance with the 2-IHS results. It can be acknowledged that old soil-water likely plays an important role in snowmelt freshet, which cannot be appreciated with the two-component analysis since isotopic homogeneity is assumed between soil water and groundwater.

Streamflow Recession Modelling

The present study used the dual-linear reservoirs model developed by Moore (1997) to compute the master recession curves of Stephen's Creek headwater catchment and Roberts Creek watershed based on 8 recession segments.

$$Q_t = Q_0 e^{-\phi_2 t} + \frac{\phi_2 Q_1}{\phi_2 - \phi_1} \cdot \left(e^{-\phi_1 t} - e^{-\phi_2 t}\right) \qquad (4)$$

where ϕ_1 and ϕ_2 are the mathematical representations of the upslope and footslope zones and where Q_0 and Q_1 are parameters representing outflow for an initial volume of water in the reservoir(s) and must be determined for each recession segment. The calibration of all parameters was done iteratively by minimizing a loss function using Powell's method as adapted by Moore (1997). For comparability, the master recession parameters ϕ_1 and ϕ_2 for dual-linear reservoirs can be transformed with the following equation in order to obtain constants (k) within the range usually reported in the literature (0.5−1.0):

$$k_{1,2} = \exp(-\phi_{1,2}) \qquad (5)$$

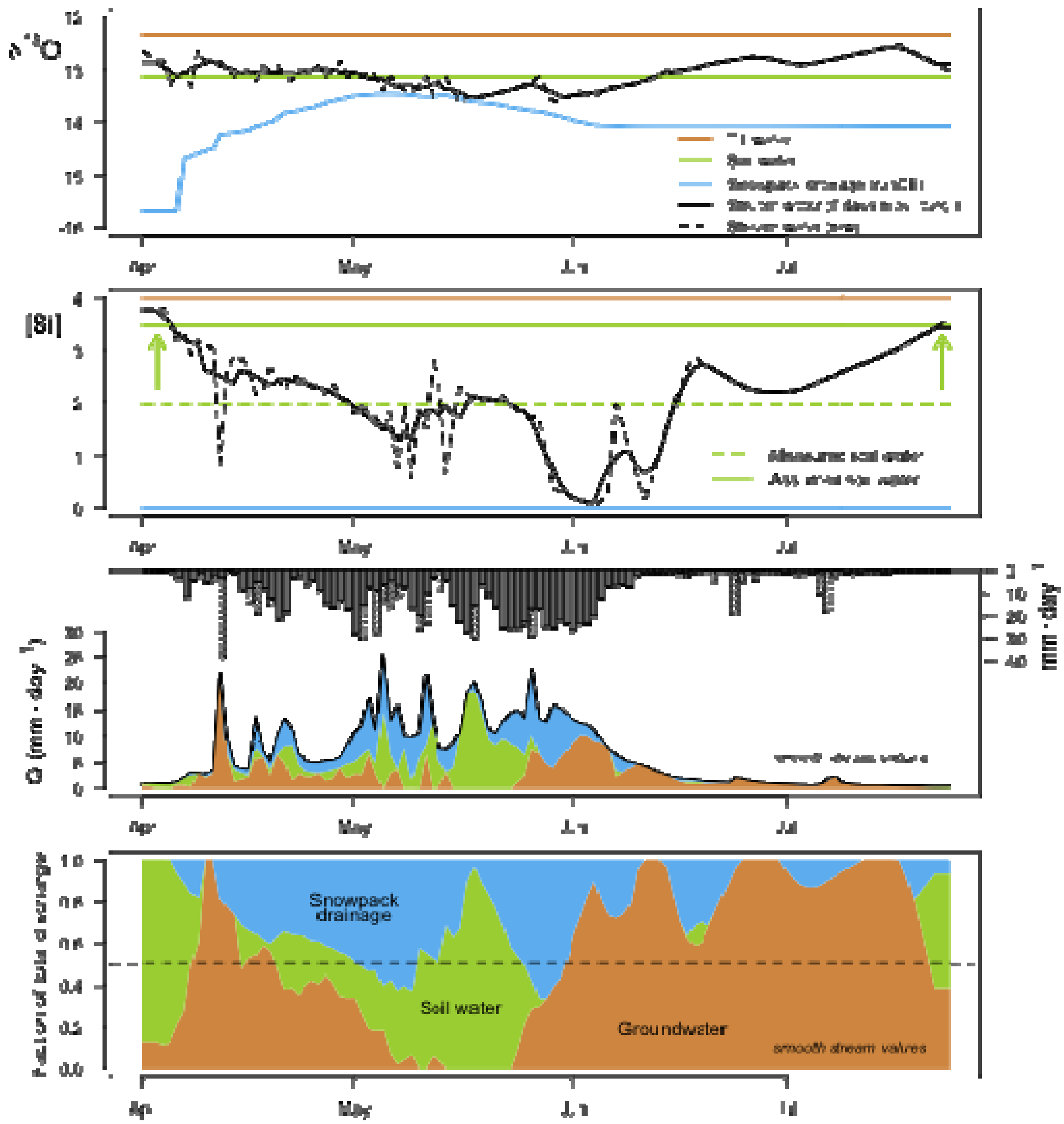

Figure 5. Three-component hydrograph separation using an assumed silicon concentration to define the soil water component. Upper two graphs show component and stream concentrations for both tracers; the 2nd lower graph shows the hydrograph separation and the most lower graph shows the corrected fraction of groundwater, soil water and snowpack water in the streamflow for smothered stream concentrations.

Based on reconnaissance field visits and given the proximity of the two gauging stations, the watersheds are assumed to share the same geological, pedological and vegetative characteristics as well as similar climatic variables. The main identifiable difference between both watersheds is that the Stephen's Creek runoff regime is dominated by a much larger snowmelt component during the spring as opposed to Roberts Creek, which is mainly rainfall-dominated over the winter.

The recession characteristics of the upslope and footslope representations of the catchment vary similarly for both watersheds. The upslope contribution can be interpreted as draining hillslopes after an event—the *k* constant for the upslope zone is 0.22 and 0.20 for Stephen's Creek and

Roberts Creek respectively. The footslope contribution is interpreted as being the groundwater and riparian contributions (i.e. baseflow) and has a *k* constant of 0.92 and 0.89 for Stephen's Creek and Roberts Creek respectively. Both recession constants are higher for Stephen's Creek headwater, which means that the daily discharge differential is more accentuated at Roberts Creek at the mouth. Although it is difficult to statistically assess the significance of these small differences in *k* values, if these are validated this would mean that Stephen's Creek headwater catchment generally supports a steadier baseflow than a larger basin such as Roberts Creek, which is an unexpected outcome.

DISCUSSION AND CONCLUSION

Saturated throughflow (or interflow) is a runoff process that occurs where decreasing hydraulic conductivity with depth has a controlling effect on streamflow response. Hutchinson and Moore (2000) showed its prevalence during rainfall events in a B.C.'s forested catchment with shallow soil underlain by impervious basal till. Because rainfall events are short-lived and generally assumed to be more intense than snowmelt events, it was unclear if saturated throughflow had the same dominating role during the freshet, or if matrix-dominated diffuse processes in near-stream zones (i.e. piston-flow or translatory flow) are preponderant. Hydrometric results paired with isotopic analysis suggest that saturated throughflow is also the dominant runoff mechanism at play during spring freshet in this environment.

Event water dominating the streamflow is an unusual outcome in IHS studies. Sueker *et al.* (2000) conducted a 2-IHS and a 3-IHS study in three Colorado headwater catchments physically similar to Stephen's Creek during a comparable snowmelt season in terms of magnitude (3 to 4 months long). The authors found that pre-event water was dominating the streamflow during the early spring (~ 50%), while event water was the main contributor during the peak melt in June (up to 76%). Those results are similar to ours and are interpreted as an initial migration of most pre-event subsurface water during the early season followed by a gradual replenishment of the subsurface storage by snowmelt water. The percentage of event water was significantly higher in the headwater catchment in July, suggesting that snowmelt can efficiently recharge the deep riparian flow-paths contributing to summer baseflow, even if saturated throughflow is the dominant runoff mechanism. This would be in contradiction with isotopic evidences obtained by Laudon (2004) in a Swedish watershed, who reported that deep flow path (>90 cm deep) at a section located 4 m away from the stream was not affected by snowmelt input. It is argued that the much larger volume of snowmelt observed in B.C.'s coastal landscape may explain the disparity between the sites. Despite the large uncertainty, mass balance estimates in the headwater catchment support these results by suggesting that subsurface reservoirs carried over a net gain from the freshet, even after the dry season has ended. Recession analysis between Stephen's Creek and Roberts Creek implies that the small snowfed headwater catchment could sustain a given baseflow for a longer period of time than the larger rainfall-dominated watershed. It is proposed that the storage capacity of the headwater catchment is likely smaller, but its riparian reservoirs were saturated at the onset of the summer due to the extensive snowmelt season, as opposed to Roberts Creek, resulting in an enhanced capacity to support baseflow during late summer. However, the role of evapotranspiration between the headwaters and the lower areas of the watershed should be better characterized in order to dissipate the ambiguity of this finding.

The results presented in this study are empirically demonstrating the linkages between spring freshet and deep flow-paths in B.C.'s coastal environment. It is concluded that climate change will most likely reduce late summer water yield in watersheds that are currently considered "hybrid". The absolute decrease in streamflow is unknown but could be significant, especially during years with high summer evapotranspiration. Water conservation programs have been proven successful to control water demand growth, but multiple approaches should be considered in order to secure a sustainable water supply for the communities and a viable aquatic environment in exploited creeks.

REFERENCES

Buttle JM. 1998. Fundamentals of small catchment hydrology, in: Kendall C and McDonnell JJ [Eds.]. *Isotope Tracers in Catchment Hydrology*, Elsevier, Amsterdam, pp.1−49.

Cooper LW. 1998. Isotopic fractionation in snow cover, in: Kendall C and McDonnell JJ [Eds.]. *Isotope Tracers in Catchment Hydrology*, Elsevier, Amsterdam, pp.119−136

Cornelis JT, Ranger J, Iserentant A, Delvaux B. 2010. Tree species impact the terrestrial cycle of silicon through various uptakes. *Biogeochemistry* **97**: 231−245.

Eaton B, and Moore RD. 2010. Chapter 4—Regional Hydrology in: Pike RG, Redding TE, Moore RD, Winker RD, and Bladon KD [Eds.], Compendium of Forest Hydrology and Geomorphology in British Columbia, B.C. Ministry of Forest and Range, Forest Science Program, Victoria, B.C. and FORREX Forum for Research and Extension in Natural Resources, Kamloops, B.C. Land Management Handbook, **66**, URL: http://www.for.gov.bc.ca/hfd/pubs/Docs/Lmh/Lmh66.htm

Environment Canada. 2010. AHCCD and HYDAT databases, Meteorological Services of Canada, Ottawa, Canada, available online: http://www.ec.gc.ca

Federer CA, Vörösmarty C, and Fekete B. 2003. Sensitivity of annual evaporation to soil and root properties in two models of contrasting complexity. *J. of Hydromet.* **4**: 1276−1290.

Genereux D. 1998. Quantifying uncertainty in tracer-based hydrograph separation. *Water Res. Res.* **34**: 915−919.

Goodison BE, Ferguson HL, and McKay GA. 1981. Measurement and data analysis, in: Gray DM, and Male DH [eds]. *Handbook of Snow: Principles, Processes, Management and Use*, Pergamon Press, Willowdale, pp.191−265.

Hinton MJ, Schiff SL, and English MC. 1994. Examining the contributions of glacial till water to storm runoff using two- and three-component hydrograph separation. *Water Res. Res.* **30**(4): 983−993.

Hutchinson DG, and Moore RD. 2000. Throughflow variability on a forested hillslope underlain by compacted glacial till. *Hydro. Proc.* **14**: 1751−1766.

Jost G, Moore RD, Smith R, and Gluns DR. *submitted*. Distributed temperature index snow melt modeling for forested watersheds. *J. of Hydro.*

Kendall KA, Shanley JB, and McDonnell JJ. 1999. A hydrometric and geochemical approach to test the transmissivity feedback hypothesis during snowmelt. *J. of Hydro.* **219**: 188−205.

Kim HJ, Sidle RC, Moore RD, and Hudson R. 2004. Throughflow variability during snowmelt in a forested mountain catchment, coastal British Columbia, Canada. *Hydro. Proc.* **18**: 1219−1236.

Krabbenhoft DP, Browser CJ, Anderson MP, and Valley JW. 1990. Estimating groundwater exchange with lakes, 1, The stable isotope mass balance method. *Water Res. Res.* **26**: 2445−2453.

Laudon H, Hemond HF, Krouse R, and Bishop KH. 2002. Oxygen 18 fractionation during snowmelt: Implications for spring flood hydrograph separation. *Water Res. Res.* **38**(11): 1258. doi:10.1029/2002WR00510

Laudon H, Köhler S, Seibert J, and Bishop KH. 2004. Hydrological flow paths during the spring flood: Congruence between hydrometric measurements and oxygen-18 in snowmelt, soil water and runoff. *Water Res. Res.* **40**(3): W03102. doi:10.1029/2003WR002455

Laudon H, Sjöblom V, Buffam I, Seibert J, and Mörth M. 2007. The role of catchment scale and landscape characteristics for runoff generation of boreal streams. *J. of Hydro*. **344**: 198−209.

Markoff MS, and Cullen AC. 2007. Impact of climate change on Pacific Northwest hydropower. *Climatic Change* **87**: 451−469.

Mast AM, Kendall C, Campbell DH, Clow DH, and Black J. 1995. Determination of hydrological pathways in an alpine-subalpine basin using isotopic and chemical tracers, Loch Vale Watershed, Colorado, USA. *IAHS Publ.* **228**: 263−270.

McHale MR, McDonnell JJ, Mitchell MJ, and Cirmo CP. 2002. A field-based study of soil water and groundwater nitrate release in an Adirondack forested watershed. *Water Res. Res.* **38**(4): 1031, doi:10.1029/2000WR000102

Mielko C, and Woo MK. 2006. Snowmelt runoff processes in a headwater lake and its catchment, subarctic Canadian Shield. *Hydro. Proc.* **20**: 987−1000.

Moore RD. 1989. Tracing runoff sources with deuterium and oxygen-18 during spring melt in a headwater catchment, southern Laurentians, Québec. *J. of Hydro.* **112**: 135−148.
Moore RD. 1997. Storage-outflow modelling of streamflow recessions, with application to a shallow-soil forested catchment. *J. of Hydro.* **198**: 260−270.
Moore RD. 2005. Slug injection using salt in solution. *Streamline Watershed Management Bulletin* **8**(2): 1−6.
Moore RD, Allen DM, and Stahl K. 2007. Climate change and low flows: Influence of groundwater and glaciers. *Final Report for Climate Change Action Fund, N.R.C.*, Project A875, 201pp.
Rodenhuis D, Bennett KE, Werner AT, Murdock TQ, and Bronaugh D. 2007. Climate Overview 2007: Hydro-climatology and future climate impacts in British Columbia. *Pacific Climate Impacts Consortium 2007 report*, Victoria, Canada, available online: http://pacificclimate.org/docs/publications/PCIC.ClimateOverview.pdf
Rodhe A. 1998. Snowmelt-Dominated Systems, in: Kendall C, and McDonnell JJ.[Eds.]. *Isotope Tracers in Catchment Hydrology*, Elsevier, Amsterdam, pp.391−433.
Snover AK, Hamlet AF, and Lettenmaier DP. 2003. Climate change scenarios for water planning studies—pilot applications in the Pacific Northwest. *Bull. of the Am. Meteo. Soc.* **84**(11): 1513−1518.
Sueker JK, Ryan JN, Kendall C, and Jarrett RD. 2000. Determination of hydrologic pathways during snowmelt for alpine/subalpine basins, Rocky Mountain National Park, Colorado. *Water Res. Res.* **36**(1): 63−75.
Whitfield PH. 2001. Linked hydrologic and climate variations in British Columbia and the Yukon. *Env. Monit. and Assess.* **67**: 217−238.
Whyte DM. 2004. Hydrologic response during snowmelt in three steep headwater catchments: Ringrose Slope, Slocan Valley, British Columbia. *M.Sc. thesis – geography*, Department of Geography, University of British-Columbia, unpublished.