THE HYDROLOGIC SIGNIFICANCE

OF LATERAL WATER FLOW THROUGH SNOW

by

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A thesis

submitted in partial fulfillment

of the requirements for the degree of

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The following individuals read and discussed the thesis submitted by student David Parker Eiriksson, and they evaluated his presentation and response to questions during the final oral examination. They found that the student passed the final oral examination.

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ABSTRACT

Understanding the mechanisms by which catchments route vertical water inputs laterally to stream channels is central to the development of accurate predictive models of watershed processes. It is commonly assumed that lateral redistribution occurs as overland or subsurface flow. Lateral flow can also occur within the snowpack during rain-on-snow (ROS) events or spring melt, sometimes resulting in surface expressions commonly called “runnels.” This thesis examines lateral flow through snow and the role of the snowpack as a rapid down-slope water delivery mechanism, with the goal of determining if lateral flow through snow is an important control on streamflow generation and soil moisture.

To quantify the flux of lateral flow through snow, we installed two identical 4 m^2 snowmelt lysimeters side-by-side on a 20 degree slope in the snow dominated Dry Creek Experimental Watershed, near Boise, Idaho. One lysimeter was blocked from lateral upslope inputs (control site) while the second lysimeter was not (experimental site). Both lysimeters were blocked on the downslope side. The experiment was designed so the total volume of water routed laterally through the snowpack could be estimated from the difference between the two plots. Through the 2010-2011 snow season, the experimental lysimeter collected ~47% more meltwater than the control lysimeter with ~34% of the total difference between the plots occurring during one major ROS event in mid-January, 2011. Further, results of a snow vs. soil tracer comparison provide evidence that the

snowpack serves as an effective down-slope water delivery mechanism that may help contribute to streamflow generation and soil moisture variability.

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1 INTRODUCTION

Understanding the mechanisms by which catchments route vertical water inputs laterally to stream channels is central to the development of accurate predictive models of watershed processes. Rain and snowmelt are classically conceptualized as vertical inputs to the soil that are routed laterally via overland or subsurface flow. While this conceptual model is appropriate in the case of rain water inputs, it is well known within the snow science community that water can be routed laterally through seasonal snowpacks during spring melt and rain-on-snow (ROS) (e.g., Kattelmann and Dozier, 1999; Peitzsch, 2009; Singh *et al.*, 1997; Wankiewicz, 1979; Whitson, 2009). Despite this, snowmelt models used for hydrologic modeling purposes assume one dimensional water percolation through the snowpack (e.g., Marks *et al.*, 1999) and lateral flow is typically viewed as an impedance to vertical infiltration rather than an important mechanism itself. With this premise in mind, the following thesis discusses the hydrologic significance of lateral flow through snow and the role of the snowpack as a rapid down-slope water delivery mechanism.

To understand meltwater movement through snow, dye tracers are commonly utilized. The use of dye tracers is so ubiquitous that Schneebeli (1995) remarked that such studies are "as old as snow science itself." Seligman (1936) is often credited as the first to publish results of a dye tracer experiment. He highlighted the effects of the reduced permeability of ice layers on infiltrating water. Since this first effort, numerous researchers (Gerdel, 1954; Marsh and Woo, 1985; Peitzsch, 2009; Schneebeli, 1995; Waldner *et al.*, 2004; Williams *et al.*, 2010; Woo *et al.*, 1982) have performed similar experiments and documented the movement of dye tracers through snow. While the specific objectives and techniques have evolved through the years, most snowmelt pathway studies emphasize the complexity of the process and the importance of preferential flow pathways (finger flow) rather than uniform matrix flow. In sloping terrain, ice layers, grain-size boundaries, and differences in layer wetness complicate flow pathways by creating conductivity contrasts that facilitate slope-parallel water movement through the snowpack. While not extensively studied, some researchers (e.g., Gerdel, 1954; Higuchi and Tanaka, 1982; Wankiewicz, 1979; Williams *et al.*, 2000) have documented dendritic rills on snow surfaces and interpreted their occurrence as evidence for slope-parallel water movement. Others have highlighted the importance of lateral flow through snow in the occurrence of wet slab avalanches (e.g., Peitzsch, 2009).

Traditionally, lateral flow in snow was believed to occur exclusively along ice layers (e.g., Seligman, 1936). However, several researchers (Kattelmann and Dozier, 1999; Waldner *et al.*, 2004; Wankiewicz, 1979; Whitson, 2009) have observed lateral flow in a snowpack with no prominent ice layers, and have shown that capillary barriers, formed in response to grain-size contrasts, are important impediments to infiltration. Kattelmann and Dozier (1999) downplayed the importance of ice layers for lateral flow, noting that in the Sierras, such features can have the appearance of “swiss cheese” with 50-70% of total ice area comprised of holes. These findings are in agreement with those of Whitson (2009), who observed appreciable lateral dye movement in a snowpack lacking significant ice layers. Wankiewicz (1979) offered the oft-cited Flow Impeding, Neutral, or Accelerating (FINA) conceptual model as a framework for understanding flow pathways in snow. His model indicates that the pore pressure in the snowpack on either side of a stratigraphic boundary will result in impeding, neutral, or accelerating conditions for infiltrating water. In the event of an impeding boundary in sloping terrain, Wankiewicz (1979) predicts a downslope component of flow through the snowpack.

While previous investigations into meltwater pathways successfully documented the occurrence of lateral flow in snow, most did not quantify the flux of water downslope during spring melt and ROS, partially because of the difficulty of measuring flux quantitatively. Because of this, it remains unclear whether lateral flow in snow is a hydrologically significant phenomenon. Higuchi and Tanaka (1982), English et al. (1986), and Ohara et al. (2011) are the only studies, to our knowledge, that have attempted to quantify the downslope flux of water through the snowpack.

Higuchi and Tanaka (1982) inserted gutters into snowpit walls and measured outflow from snowpack rills that ranged from 0 cm^3 cm^{-2} - .12cm^3 cm^{-2}. English et al. (1986) installed a 100 m by 10 m snowmelt lysimeter on a 20 degree slope in Ontario, Canada. Outflow from the snowpack was measured in 5 separate subplots on the hillslope in order to understand the downslope flux of both water and various chemical constituents. Snow water equivalent (SWE) measurements near each of the subplots were compared to the total melt volume collected from each subplot. The subplot nearest the base of the hill measured significantly more melt-water than was predicted from manual SWE measurements. English et al. (1986) attributed this behavior to mid-pack lateral water redistribution and suggested that well-developed ice lenses in the snowpack were the cause. More recently, Ohara et al. (2011) measured significant overland flow in a study site that was characterized by highly conductive, unfrozen soils (i.e., conditions that would not typically promote classic Hortonian overland flow). They concluded that the measured overland flow was a result of meltwater movement at the base of the snowpack held above the ground surface by capillary suction.

The hydrologic relevance of water movement through snow during ROS is also significant due to the high discharge, short lag times, and frequent flooding associated with such events (Harr, 1981; Marks *et al.*, 1998; McCabe *et al.*, 2007). McCabe et al. (2007) cites representation of ROS processes as one of the major factors contributing to flood forecast model uncertainty. To better understand ROS processes, Whitson (2009) and Singh et al. (1997) simulated rainstorms with dyed water and observed the resulting flow pathways and snowpack response. Both studies show that rain water does not typically infiltrate through the snowpack to the ground, rather, it travels to conductivity barriers within the pack where it is subsequently stored, or rapidly transmitted laterally. Whitson (2009) and Ohara et al. (2011) suggest that the snowpack may serve as a rapid downslope water delivery mechanism during ROS. This interpretation is further supported by watershed models that under-predict discharge during major ROS events (e.g. Stratton *et al.*, 2009). It is possible that these models fail to capture peak flow in part due to their inability to represent rapid water delivery through the snowpack to stream channels.

The goal of this study is to understand the hydrologic significance of lateral flow through snow and the role of the snowpack as a rapid down-slope water delivery mechanism. We define a “hydrologically significant” quantity of lateral flow through snow as a measurable downslope water flux that contributes to streamflow and has the potential to contribute to the spatial variability of soil moisture. Herein we present the results of field measurements conducted during the 2010-2011 snow season in the snow dominated Dry Creek Experimental Watershed, located just outside of Boise, Idaho. Snowmelt lysimeters and tracer experiments were utilized to document both the lateral flux of water moving downslope through the snowpack during spring melt and mid-winter rain on snow, and the relative velocities of water moving through the snowpack and soil. The results of our field work lead us to conclude that lateral water flow through snow *is* an important downslope routing mechanism that may serve as a significant control on streamflow generation and the spatial variability of soil moisture, particularly during rain on snow.

2 SITE DESCRIPTION

This majority of this study was conducted in, and adjacent to, the small (.02 km^2) Treeline Catchment (described in detail by Williams et al. (2009) and McNamara et al. (2005)) located within the larger Dry Creek Experimental Watershed, just outside of Boise, Idaho (Figure 1). The Treeline Catchment is oriented northwest-southeast and located at a mean elevation of 1620 m with 70 m of total relief. It has two small tributaries that contribute to one main ephemeral channel that typically begins flowing in late autumn and ceases in late spring or early summer. The total stream network length is approximately 250 m and is gauged with a v-notch weir. The catchment contains standard meteorlogic instrumentation, several ultrasonic snow depth sensors, and numerous soil moisture pits.

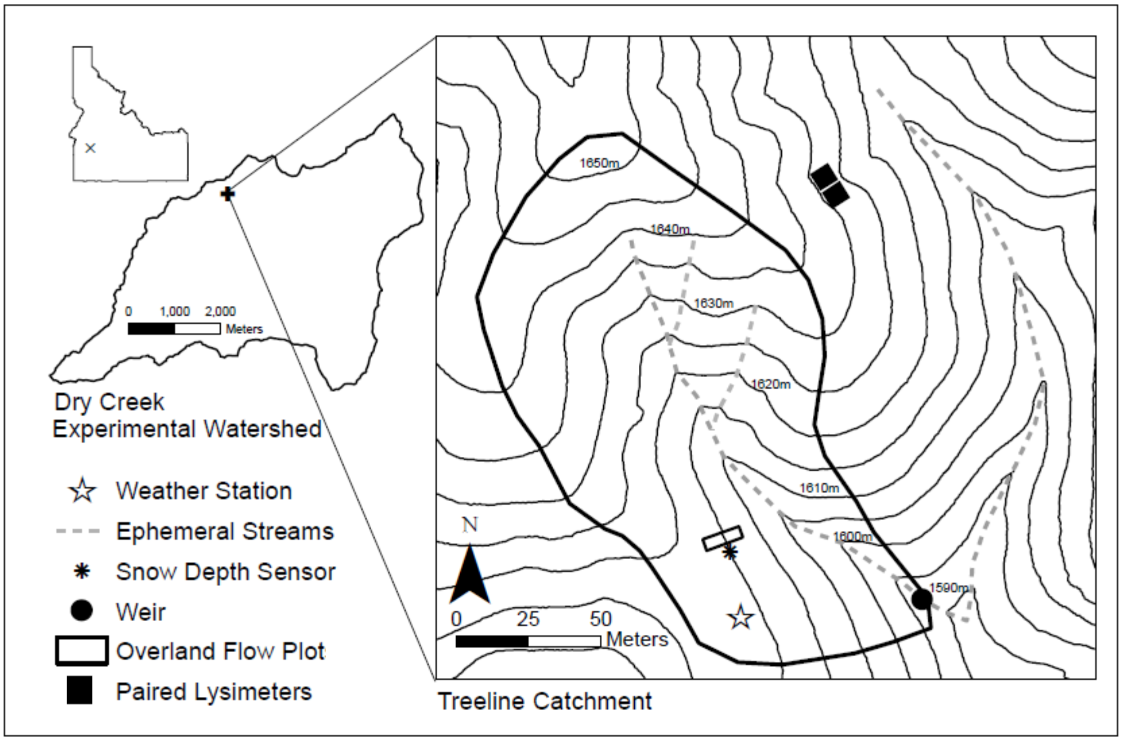

Figure 1. Location and instrumentation of the Treeline Catchment and surrounding area.

The Treeline Catchment is also instrumented with an overland flow runoff plot located on the northeast-facing slope (Figure 1). Overland flow is collected from an isolated 3x10 m area and routed to an 1893 L livestock tank (Figure 2). Stage is continuously monitored in the tank and converted to volume. Similar to the design of Ohara et al. (2011), the overland flow plot at the Treeline Catchment is designed to accept any lateral flow that occurs along the ground surface. Although not part of the original design, this plot also collects flow occurring within the bottom 11 cm of the snowpack (Figure 2). For the purposes of this thesis, we reserve the term “overland flow” for classic infiltration excess Hortonian overland flow only (Horton, 1935). Flow through, or at the base of, the snowpack while still *over land* will be referred to specifically throughout this discussion.

Figure 2. Overland flow runoff plot. The plot collects water moving along the ground surface or in the bottom 11 cm of the snowpack.

During most winters (including 2010-2011), the Treeline Catchment is located near the rain-snow transition elevation. Snow depths reported in this thesis were measured on the northeast-facing slope with a Judd Communications ultrasonic depth sensor (Figure 1). During the 2010-2011 snow season, a permanent snowpack persisted on the northeast-facing slope from 11/18/10 to 4/12/11 with an average depth of 30-50 cm and maximum depth of about 80 cm recorded during mid-December (Figure 3d). In contrast to the northeast-facing slope, the increased solar radiation on the southwest-facing slope promoted the development of a transient snowpack that accumulated and melted several times throughout the winter months.

Discharge from the Treeline Catchment during the winter and spring of 2010-2011 (Figure 3b) ranged from 0 L min^{-1} to a peak of 505 L min^{-1} that was associated with a significant ROS event that yielded 53 mm of rain over a 27-hour period on January 15-17. Following the method of Marks and Wintstral (2007), precipitation phase was determined with a 0° C dewpoint temperature threshold (Figure 3a). Precipitation data was processed using the standard World Meteorological Organization gauge catch correction equations for rain and snow (Dingman, 1994). Near surface, volumetric soil moisture (Figure 3c) was in the “wet, low-flux” state described by McNamara et al. (2005) for the majority of the winter with an average value of ~.15. In early March, the soil moisture state transitioned to the “wet, high-flux” condition (McNamara et al., 2005) with peak moisture of ~.22. At no point during the 2010-2011 snow season were frozen soil conditions observed in the Treeline Catchment.

Due to the shallow snowpack and transitional nature of the study site, we observed limited snowpack stratigraphy during the 2010-2011 snow season. The snowpack was typically dominated by .25-1 mm rounds with the occasional weak melt-freeze crust and faceted layers. The most persistent stratigraphic feature was a basal ice layer that we observed from late January to late March on the northeast-facing aspect.

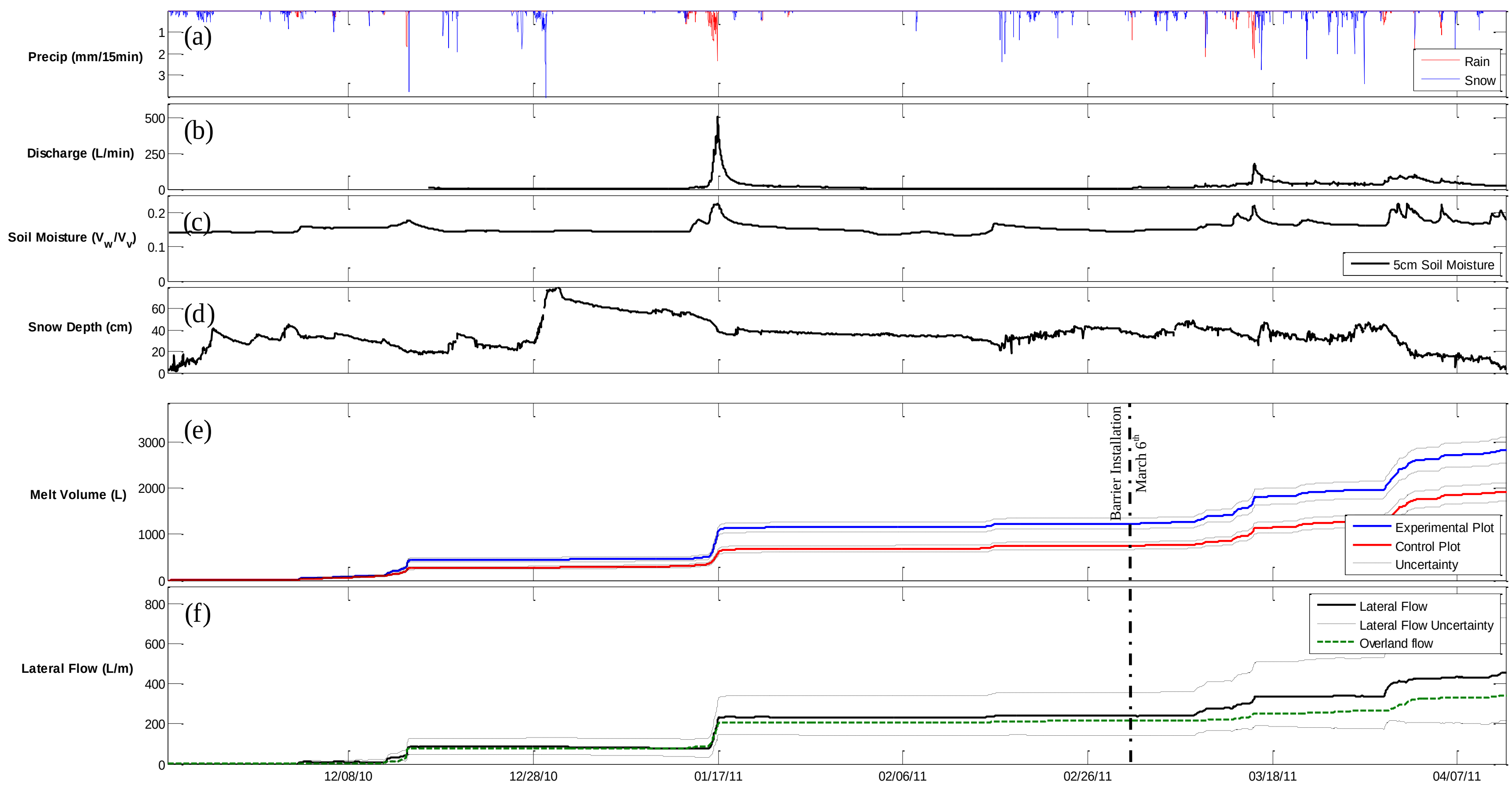

Figure 3. Summary of Treeline Catchment hydrology (a-d) and paired lysimeter experiment (e-f) results. (a) Shows precipitation intensity and phase. (b) Shows discharge from the Treeline catchment measured at the Treeline weir. (c) Is near surface volumetric moisture content. (d) Shows snow depth. (e) Shows cumulative melt for each collection plot. (f) Shows the difference between the two plots (interpreted to be the lateral flux through the snowpack) and overland flow measurements. The uncertainty in both plots was calculated assuming a tipping bucket error of ± .97ml tip^{-1}.

3 METHODS

3.1 Paired Lysimeter Experiment

To quantitatively measure the flux of lateral flow through the snowpack, we installed two adjacent 4 m^2 (2x2 m) snowmelt lysimeters on a northeast (30°) facing, 20 degree hillslope adjacent to the Treeline Catchment (Figure 1, 4a-d). This installation is referred to throughout this thesis as the paired lysimeter experiment. On March 6, 2011, impermeable, plastic-lined plywood barriers were inserted into the snowpack to control the meltwater flow into each lysimeter (Figure 4d). One lysimeter was blocked from lateral upslope inputs (control plot) while the second lysimeter was not (experimental plot). Both plots were blocked on the downslope side to prevent meltwater from exiting the collection area. Implicit in this experimental design is the null hypothesis that the experimental and control volumes should be equal if lateral flow is *not* hydrologically significant. If the experimental plot collects more water than the control plot, we can conclude that the effective collection area of the experimental plot is larger than the effective collection area of the control plot (i.e., a measurable amount of water is sourced some distance upslope).

Lysimeter sides are ~20 cm high by 2 m long, constructed out of lumber, and lined with thick polyethylene plastic sheeting (Figure 4a). Meltwater was routed to a downslope corner of each plot where it was piped two feet underground through four-inch drain pipes to tipping bucket rain gauges housed in a plywood box and buried four feet below ground surface (Figure 4b). Cumulative tips were logged every 15 minutes on a Campbell Scientific CR800 data logger. Because pipes were buried and tipping buckets housed underground, minimal blockages due to ice buildup occurred during the snow season. Great care was taken throughout the winter to avoid disturbing the snow upslope from the lysimeter collection area in order to preserve the natural snow stratigraphy.

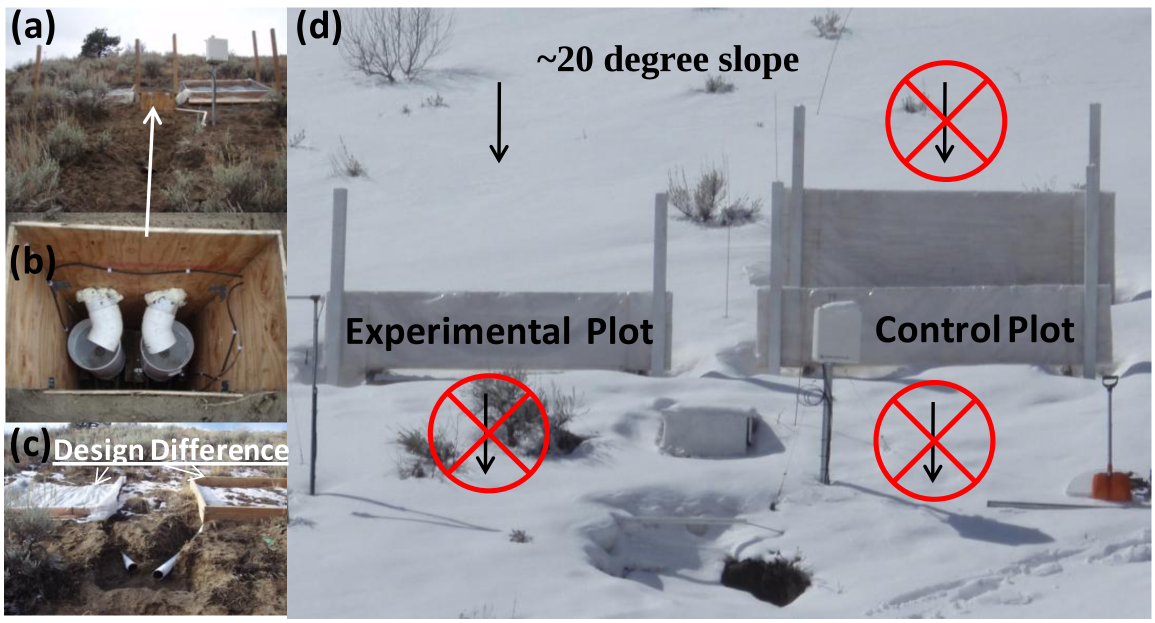

Figure 4. Paired lysimeter experiment photos. (a) Shows the paired lysimeter experiment prior to snowfall. (b) Shows the tipping buckets and plywood housing. (c) Highlights the design difference on the upslope edge of the two plots. (d) Shows the completed experiment during winter.

The tipping bucket gauges used in this experiment were originally designed to accurately measure small precipitation volumes, not large meltwater volumes sourced from a 4 m^2 collection plot. During high flow rates, the buckets cannot tip fast enough and some water is consequently spilled and not measured. To correct for this, we developed a calibration curve in the lab that relates tips 15 min^{-1} to the volume of water required per tip (Figure 5). We determined the relationship to be linear over the range of our data (r^2=.87) and calculated an RMSE of .97ml/tip using a ‘leave one out’ cross validation technique (Martinez & Martinez, 2002). We applied this linear relationship and calculated uncertainty to all snowmelt data presented herein.

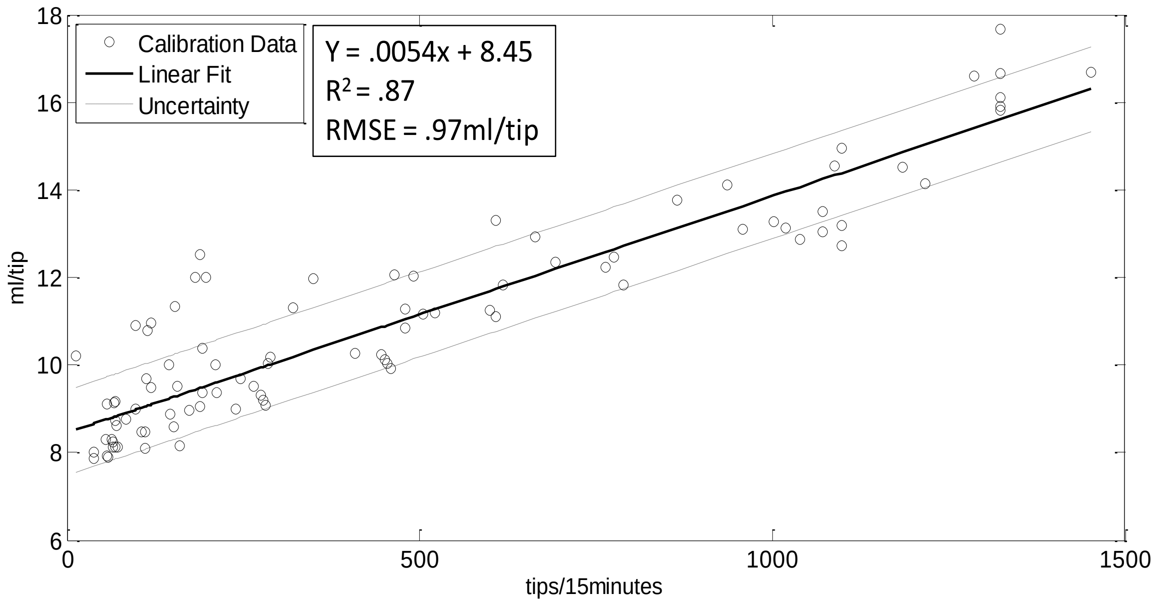

Figure 5. Tipping bucket calibration data.

The total volume of water routed downslope through the snowpack was calculated by subtracting the control plot volume from the experimental plot volume. While this approach allows us to quantitatively assess the volume of lateral flow, it is difficult to accurately determine the length scale of the upslope contributing area. Because of this, rather than reporting snowmelt depth, we present lateral flow data in the units of lateral flow volume (m^3) per unit collection area width (m). We applied the same approach to overland flow measurements.

We waited until maximum snow accumulation (March 6th) before inserting the barriers in order to minimize snowpack disturbance and artificial melt due to increased longwave radiation and also to ensure natural snowpack accumulation (Figure 3e-f). After the March 6th installation, as expected, we observed some artificial melt caused by the barriers. Note that because two barriers (upslope and downslope) were installed on the control plot and only one (downslope) on the experimental plot, the control plot melted out slightly faster than the experimental plot. The difference in melt timing complicates our ability to interpret individual melt and lateral flow events, particularly after April 2nd. After this date, we determined melt rate differences to be too extreme to accurately discuss individual melt and lateral flow events. Despite this, because we assume that the two plots collected the same amount of snow over the course of the season, we *are* confident in our cumulative season total measurements of melt and lateral flow.

We used a variety of methods to validate the above assumption, and also to assess overall lysimeter performance during the 2010-2011 snow season (11/18/10 – 4/12/11). Specifically, we performed 15 snow depth surveys between 3/12/11 and 4/5/11. On each survey date, we recorded nine snow depths in the immediate vicinity of both the experimental and control plots. In addition to verifying that the two plots collected the same amount of snow, we used these depths to ensure that the ultrasonic snow depth sensor located in the adjacent basin on a similar aspect (Figure 1) provided an accurate representation of snow depth at the paired lysimeter site. On-plot snow depths are not reported because, as noted, those depths were significantly altered by the conditions imposed by the lysimeters. As another check on the performance of the lysimeters, we compared the total snow season melt outflow to the total snow season precipitation measured by the Treeline Catchment weighing bucket precipitation gauge. This comparison is sensitive to sublimation mass loss from the snowpack, so we also examined wind speed and direction data to qualitatively determine if sublimation was an important process during the 2010-2011 snow season.

Because the lysimeters were installed in a transitional snow environment, several melt and rain-on-snow events were recorded prior to 'officially' blocking flow to the control lysimeter on March 6th. Despite this, prior to March 6th our results indicate the occurrence of lateral flow due to an intentional difference in design between the two collection plots (Figure 4c). Specifically, the control lysimeter frame is an enclosed square with ~20 cm walls on four sides, while the experimental lysimeter is only enclosed on three sides, with the upslope edge completely open and the polyethylene sheeting buried a few cm under the soil. This design allowed us to assess lateral flow in the early season prior to the development of a deep snowpack and also allowed us to capture water movement at the base of the snowpack and along the ground surface. Due to the shallow snowpack at the paired lysimeter site, snow depth was only 10 cm above the top of the lysimeter frame prior to the December 14th melt event and about 30 cm above the top of the lysimeter frame prior to the January 15-17 melt event. We interpret differences between the plots prior to the March 6th blockage to be, at a minimum, a measure of the downslope water flux through the bottom 20 cm of the snowpack.

3.2 Lateral Flow Length Scales

Central to the issue of the hydrologic significance of lateral water movement through snow is an understanding of how far laterally transported water travels during melt events and ROS. Most of our information about lateral flow length scales comes from dye tracer experiments. Whitson (2009) reported a maximum downslope dye movement of 24.3 m over a 24-hour period. Male and Gray (1981) cited evidence from dye tracer experiments and suggested that over large enough areas, the effects of heterogeneities in snowmelt processes (such as lateral and preferential finger flow) average out on the order of z^2, where z is snow depth.

A common criticism of dye tracer tests in snow is that the altered albedo imposed by the applied dye significantly alters melt dynamics and calls into question reported observations. To test the validity of this criticism, we compared the movement of the visual dye tracers, Rhodamine WT and Brilliant Blue powdered dye with a colorless rare earth element (REE) tracer solution. We also addressed the question of lateral source area by applying basic geometric analysis to the results of the paired lysimeter experiment.

3.2.1 Geometric Length Scale Analysis

With the results from the paired lysimeters, and similar to the analysis performed by Ohara et al. (2011), we utilized basic geometry to estimate minimum distances traveled by laterally routed water through, or at the base of the snowpack for eight individual snowmelt/lateral flow events thorough the 2010-2011 season. For this analysis, we conceptualized cubes of snow on top of both the experimental and control plots with length=x_1, width=y_1, and depth=z_1 (Figure 6). We conceptualized lateral flow to be sourced from an additional imaginary cube of snow upslope of the experimental plot collection area with length=x_2, width=y_2, and snow depth=z_2. Throughout this analysis, we made the assumption that $y_1 = y_2$ and that $z_1 = z_2$. Under this geometric framework, the total volume of water (V_t) collected by the experimental plot is equal to the volume of snow directly over the impermeable boundary (V_1) plus the additional, conceptualized upslope volume of snow (V_2). Note that for this analysis we make the assumption that the control plot collects a volume equal to V_1. Mathematically, the total volume of snow collected by the experimental plot is:

$$V_t = V_1 + V_2 \tag{1}$$

This expression can also be written as:

$$V_t = x_1 yz + x_2 yz \tag{2}$$

Rearranging, we can solve for the minimum upslope contributing length, x_2:

$$x_2 = \left(\frac{V_t}{V_1/x_1}\right) - x_1 \tag{3}$$

Note that these calculations yield a *minimum* estimate of contributing length because implicit in the analysis is that all additional water collected by the experimental lysimeter (V_2 in this analysis) is sourced from a snow cube of length x_2, width y_2, and depth z_2 (Figure 6).

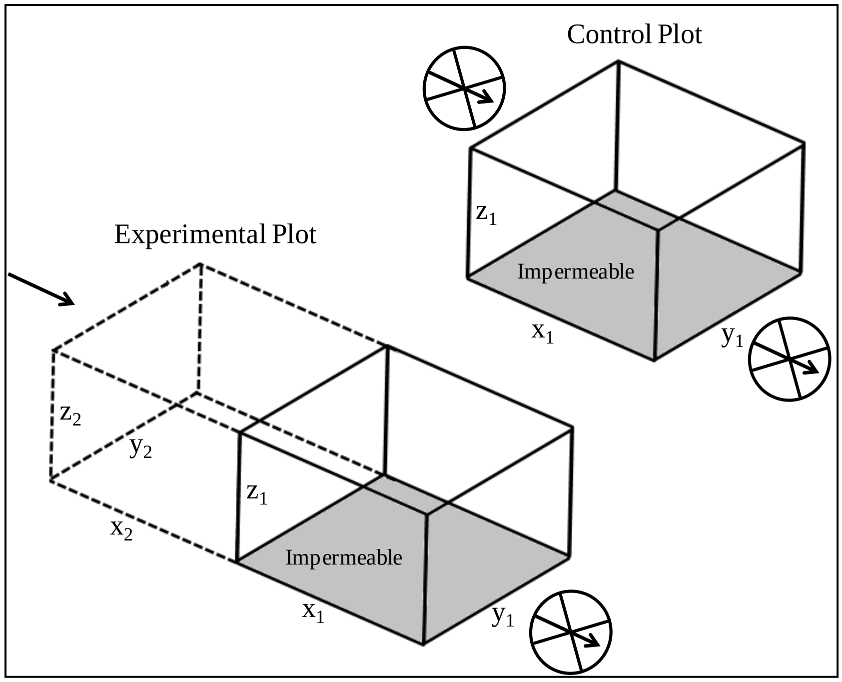

Figure 6. Conceptualized snowpack geometry for contributing length scale analysis.

<u>3.2.2 Visual and Rare Earth Element Tracer Comparison</u>

Because the premise for this research is largely based on the results of previous visual dye tracer experiments, we tested the validity of the criticism that colored tracers interfere significantly with melt dynamics. We compared the movement of the visual dye tracers, Rhodamine WT and Brilliant Blue powdered dye with a colorless rare earth element (REE) tracer solution. REEs have been used as tracers in snow by several researchers (Feng *et al.*, 2001; Lee *et al.*, 2008; Taylor *et al.*, 2001) for a variety of reasons: 1. Natural REE concentrations in snow are very low (typically <1ppb), therefore it is reasonable to assume that background concentrations are negligible. 2. REE solutions do little to alter the freezing temperature of snow (Taylor et al., 2001). 3. REEs are accurately detectable in water at low ppb levels by inductively-coupled-plasma mass spectrometer.

The experiment was conducted on 3/30/11 and 3/31/11 at a newly established snow research site within the boundaries of Bogus Basin ski area. Bogus Basin is located in the headwaters of the Dry Creek Experimental Watershed and receives an average of 5-6 m of snow per year. This site was chosen for the tracer comparison study because, unlike the Treeline site, the snowpack at the Bogus Basin site is deep and stratigraphically complex.

On March 30th, we applied each of the three tracers (Rhodamine WT, Brilliant Blue powdered dye, and samarium) to 1x.3 m plots on a 20 degree, southeast-facing slope at the Bogus Basin study site. We applied 480 ml of 1961 ppm samarium with a misting garden sprayer. Following the method of Taylor et al. (2001), solutions were prepared in the lab from REE chloride salts of 99.9% purity. To minimize artificial melt, or lateral flow induced by the introduction of water to the snowpack, solutions were kept cold prior to application and applied in the early morning hours on cold snow as suggested by Taylor et al. (2001). Additionally, solutions were applied under calm conditions to prevent wind transport of tracer solutions. Adjacent to the application of samarium, we applied 551 ml of 2108 ppm Rhodamine WT solution and 1 m line of Brilliant Blue powdered dye. One meter spacing was allowed between each of the application lines. To maintain consistent methods with Whitson (2009), we covered the Rhodamine and Brilliant Blue with several cm of fresh snow to minimize the effects of the altered albedo.

On 3/31/11, after allowing the tracers to move through the melting snowpack for approximately 24 hours, we destructively sampled all three plots by digging snow pits starting about 15 m downslope from the application point and working our way up to the application site. The Rhodamine WT and Brilliant Blue plots were qualitatively assessed visually and the samarium plot was sampled at .2, 2, 4, 6, 8, and 10 m downslope from the application point. At each of the increments downslope from the application site, we sampled every 4 cm to a depth of 32 cm with a 100 cm^3 density cutter. The decision to only sample to a depth of 32 cm was informed by the behavior of the visible dye tracers, which were never observed below this level.

To establish background REE concentrations in snow and to validate our assertion that REEs occur in extremely low natural abundances, clean snow profiles were sampled at various locations throughout the Dry Creek Experimental Watershed on 5 separate days during the winter. Clean snow was collected every 5 cm throughout the depth of the snowpack using a standard 100 cm^3 density cutter.

Snow samples for samarium analysis were transported in Ziploc bags to the lab where they were immediately filtered to 0.45 microns and acidified with a few drops of 17 M HNO_3 to ensure solution stability. Samarium was analyzed with a Thermo X Series 2 quadrupole inductively-coupled-plasma mass spectrometer (ICP-MS) at Boise State University. Samarium concentrations were calibrated using a two-point calibration from aqueous standards at concentrations of ~15 and ~150 ppb. Analytic uncertainty for samarium >0.1 ppb was better than 5%.

3.3 Snow vs. Soil "Tracer Race" Transit Time Comparison

The significant difference in hydraulic conductivity between snow (ranges from 4-1150 m/hr (Jordan *et al.*, 1999)) and Dry Creek soils (.13-.29 m/hr (Gribb *et al.*, 2009)) leads us to suspect that, under snowpack conditions favoring lateral water flow through snow, water transported through the snowpack will reach the stream channel much faster than water transported through soil. To test this hypothesis, and assess the importance of the snowpack as an efficient downslope water delivery mechanism, we applied separate tracers to both the snow surface and the soil surface, approximately 11.5 m upslope from the Treeline Catchment stream channel (Figure 7). Specifically, we applied .74 L of ~2100 ppm Rhodamine WT to a 1.5x.5 m patch of the snow surface with a misting garden sprayer. To counteract artificial melt caused by the altered albedo, we followed the method of Whitson (2009) and covered the dyed portion of the snowpack with fresh snow. Immediately adjacent to the Rhodamine WT application location, we dug to the base of the snowpack and applied 3.2 L of ~61,000 ppm NaCl to a 1.5x.5 m patch of soil. Following NaCl application, we filled in the snow pit to ensure that the tracer would be subject to natural melt conditions. Concentrations of each tracer were then continually logged at least every five minutes in the small ephemeral stream located immediately below using a Hach hydroprobe.

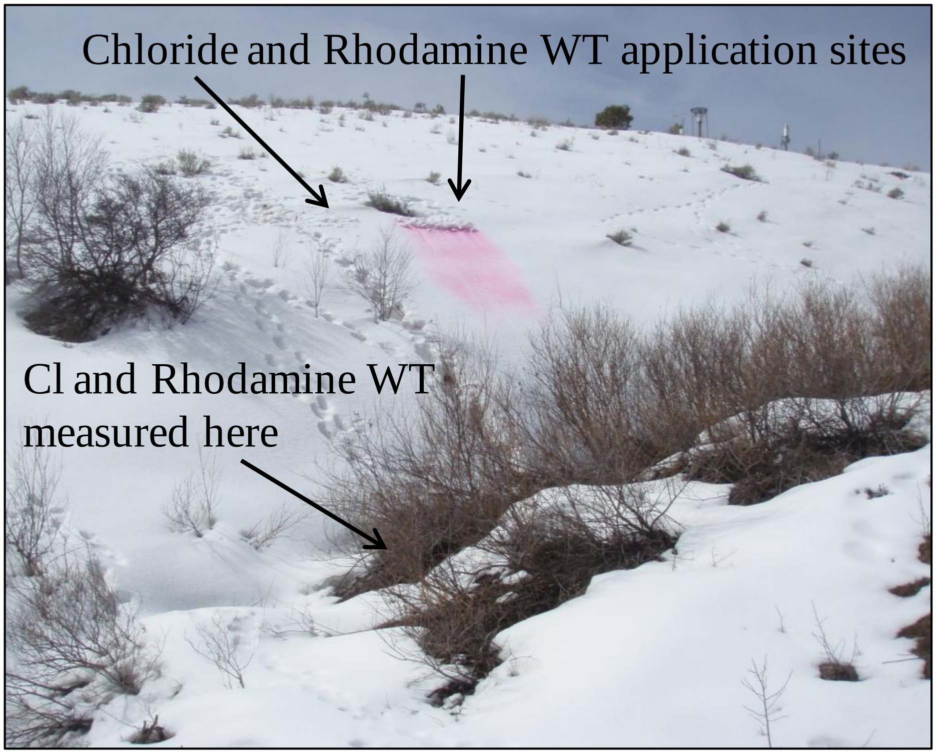

Figure 7. Tracer race experiment photograph taken one day after application. Note the visible movement of the Rhodamine WT tracer in the near surface layers of the snowpack.

4 RESULTS

4.1 Paired Lysimeter Experiment Results

The results of the paired lysimeter experiment are shown in Figure 3e-f. The Treeline Catchment snow season hydrologic and meteorologic conditions are summarized in Figure 3a-d. During the 2010-2011 snow season, the unblocked, experimental lysimeter collected a total of 2833±278 L and the blocked, control lysimeter collected a total of 1921 ±201 L (47% more than the experimental plot). Therefore, we estimate that 912±479 L, or 456±240 L m^{-1} of water was routed laterally through the snowpack during the melt season. Figure 3f shows the lateral flux per meter at the overland flow collection site and at the paired lysimeters (calculated as the difference between the experimental and control plots). Note the similarity in magnitude and timing of lateral flow through snow collected by the paired lysimeters and the overland flow plot, particularly during the mid-December and mid-January ROS events.

Prior to April 2nd (the cutoff date for examining individual lateral flow events), we recorded eight distinct melt/lateral flow events. During these events, the experimental lysimeter collected between 23.9% and 59.3% more water than the control plot (Table 1). Lateral flow was observed during all significant melt events throughout the season and all of the individual melt/lateral flow events recorded by the lysimeters coincided with some degree of rain (Table 1). The most significant melt event of the season occurred on January 15-17, when approximately 53 mm of rain fell on the snowpack over a 27-hour period. During this storm, the experimental lysimeter collected 51.6% more water than the control lysimeter (605±51 and 293±29 L m^{-1}, respectively). This single event accounted for approximately 34% of the total lateral flow observed during the snow season.

Because all significant melt events measured by the lysimeters were accompanied by rain, we performed a rough check on the relative influence that each rain event had on lysimeter outflow (Table 1). Specifically, we calculated the ratio of control plot outflow depth to rain depth for each of the melt events. Using a subjective cutoff of 2.0 (control depth to rain depth ratio), we classified four lysimeter outflow events as ‘rain dominated’ (12/14/10, 1/16/11, 3/13/11, and 3/15/11) and four lysimeter outflow events as ‘melt dominated’(12/11/10, 3/9/11, 3/30/11, and 4/1/11). This calculation was only performed using data from the control plot because the unconstrained collection area of the experimental plot made it difficult to accurately calculate melt depth.

Table 1. Summary of major melt and lateral flow events.

Lat Flow Start	Lat Flow End	Exp Vol (L)	Control Vol (L)	Lateral Flow Vol (L/m)	Collection Difference %	Rain (mm)	Control Depth (mm)	Control Depth/Rain Depth[1]
12/11/10 22:45	12/12/10 17:30	85±9	36±4	25±9	57.6	1.54	9.00	5.8
12/14/10 6:00	12/14/10 16:15	159±13	68±7	45±13	57.2	14.70	17.00	1.2
1/16/11 0:45	1/17/11 12:00	605±51	293±29	157±51	51.6	53.00	73.25	1.4
3/9/11 13:00	3/11/11 13:45	135±14	65±7	35±14	51.9	5.13	16.25	3.2
3/13/11 16:00	3/14/11 9:45	118±12	78±8	19±12	59.3	6.66	12.00	1.8
3/15/11 11:30	3/16/11 11:15	229±21	156±15	36±21	31.9	26.49	39.00	1.5
3/30/11 2:30	3/31/11 18:30	441±43	290±29	76±43	34.2	9.70	72.50	7.5
4/1/11 12:00	4/2/11 18:15	159±16	121±13	19±16	23.9	3.96	30.25	7.6

1. A subjective cutoff of 2.0 was used to delininate 'rain dominated' and 'melt dominated' events.

4.1.1 Lysimeter Data Quality Verification

Because our interpretation of the paired lysimeter results are predicated on the assumption that the experimental and control plots will collect the same amount of water in the absence of lateral flow, we used a variety of methods to verify that the two plots accumulated the same amount of snow and that the relative collection efficiency of the two plots was the same.

The results of regular snow surveys (Figure 8) performed in the immediate vicinity of each lysimeter shows that between March 12th and April 5th neither plot preferentially accumulated or melted snow–an expected result considering the close proximity of the two plots. These results also show that the ultrasonic snow depth sensor located in the basin adjacent to the paired lysimeter experiment (Figure 1) provides an accurate representation of snow depth at the paired lysimeter experiment.

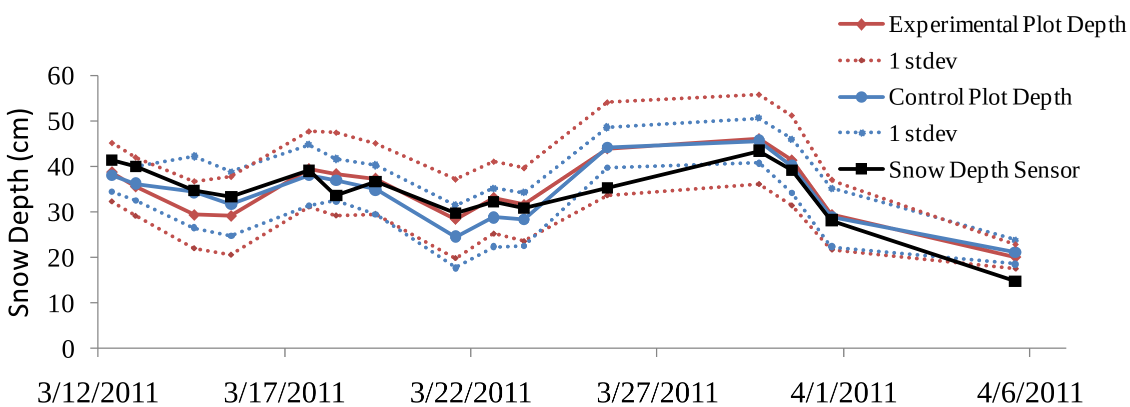

Figure 8. Control and experimental plot snow depth comparison

We also compared total precipitation to total recorded outflow by the lysimeters (Table 2). During the 2010-2011 snow season, the Treeline Catchment precipitation gauge recorded a wind corrected total of 54.01 cm of water (rain and snow combined).

We used the horizontal area (3.76 m^2) of the control plot (rather than the hillslope area of 4 m^2) to convert precipitation depth to volume. This conversion allowed us to estimate an expected melt outflow volume of 2031 L in the absence of lateral flow (i.e., the conditions imposed on the control plot). Our results (Table 2) show that the expected melt volume (2031 L) was within the uncertainty of the measured melt volume on the control plot (1921±201 L), indicating that this plot effectively represented melt conditions in the absence of lateral flow. Further, the expected melt volume was significantly less than the total experimental plot outflow volume (2833±278 L). Because the experimental plot collected more than the expected volume derived from precipitation data, we interpret that the additional water was sourced upslope and delivered to the collection plot laterally through the snowpack.

Table 2. 2010-2011 snow season precipitation summary

Total Rain (cm)[1]	16.83
Total Snow (cm)[1]	37.18
Total Precip (cm)[1]	54.01
Total Precip on Control (L)[1]	2031
Total Control (L)[2]	1921±201
Total Experimental (L)[2]	2833 ±278

1. Rain gauge data
2. Paired lysimeter experiment data

Sublimation from the snowpack is one possible source of error in the outflow-precipitation volume comparison discussed above. Because sublimation impacts meltwater outflow and not total precipitation, if sublimation is an important contributor to snow mass loss, the total precipitation volume should be larger than the total control plot outflow. Our results show that the total precipitation was within the uncertainty of the total control plot outflow (Table 2). If the uncertainty in the control plot data is ignored, our results show that a small amount (~5%) of the total snow mass at the paired lysimeter experiment was lost to sublimation. Either way, our data indicates that sublimation was not a dominant process in the Treeline Catchment during the 2010-2011 snow season. While estimates of sublimation vary widely, some researchers (Schmidt *et al.*, 1998) have estimated season total snow mass loss due to sublimation of 20% in a Colorado subalpine forest.

To support our assertion that sublimation was not a significant contributor to snow mass loss during the 2010-2011 snow season, we examined wind speed and direction data collected in the Treeline Catchment. We also compared wind data to the orientation of the paired lysimeter experiment to investigate the potential impacts that the one meter tall lateral flow barriers had on wind patterns. The results of this analysis (Figure 9) indicate that during the 2010-2011 snow season, wind in the Treeline Catchment typically blew out of the southwest at speeds less than 4 m s^{-1}. The consequence of these observations is twofold. First, because wind speed is a primary control on sublimation, it follows that the light wind conditions that dominated in the Treeline Catchment would not promote significant sublimation. Second, the northwest-southeast orientation of the one meter tall lateral flow barriers would not significantly block wind blowing out of the southeast (Figure 9). Further, we suspect that whatever sublimation did occur affected both collection plots more or less equally.

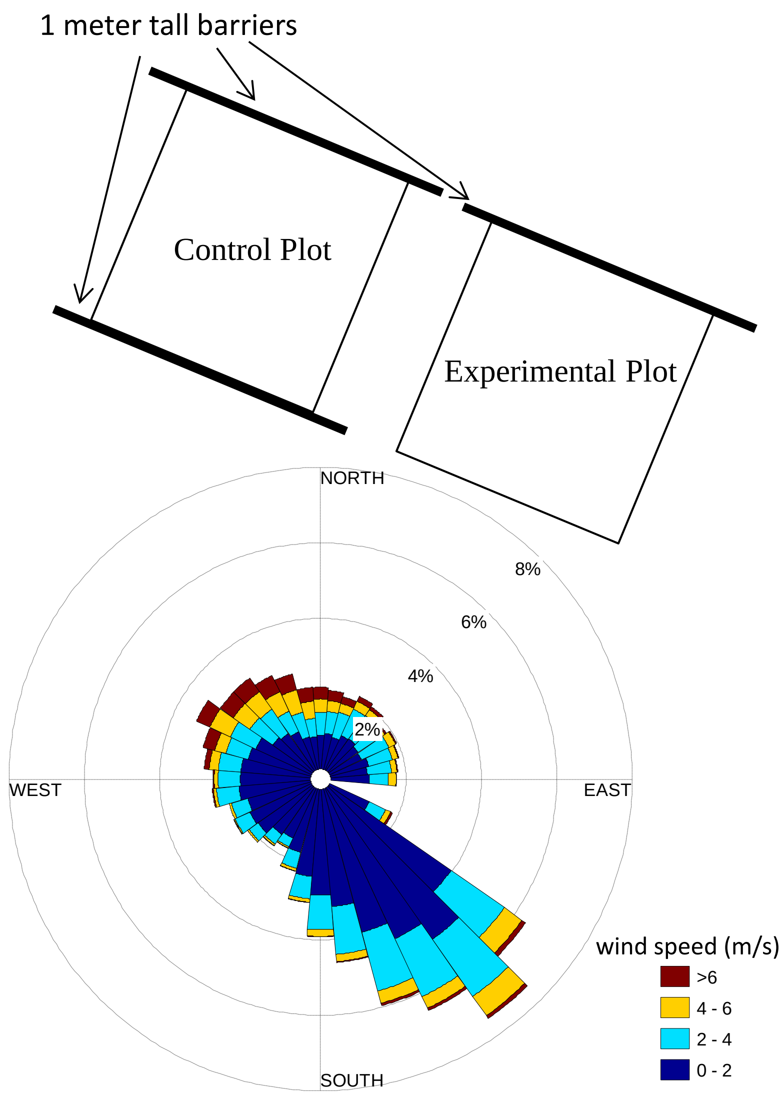

Figure 9. Summary of 2010-2011 snow season wind speed and direction. Note that the paired lysimeter schematic is oriented to illustrate the potential impacts that the lateral flow blockages had on wind and sublimation.

To demonstrate that the two plots exhibit similar collection efficiencies, we compared snow-free precipitation collection rates for 10 summer rain events. The results of this analysis (Figure 10) show that for 8 out of 10 rain events, the difference between the two plots was well within our calculated confidence intervals. We suspect that the lysimeter frame design difference between the control plot and experimental plot (i.e., the control plot has an upslope blockage and the experimental plot does not) may account for the increased experimental plot collection rates on 6/6/11 and 6/8/11. While we do not believe that Hortonian overland flow is a dominant runoff generation mechanism in the Treeline Catchment, it *is* possible that the additional water collected by the experimental plot is due to minor overland flow contributions. Specifically, we calculated necessary overland flow values of ~1.5 and .4 L m^{-1} to account for the difference between the two plots during the 6/6/11 and 6/8/11 rain events (respectively). These estimates are consistent with previously measured snow-free overland flow measurements in the Treeline Catchment. Unfortunately, due to an overland flow runoff plot malfunction during these events, we are unable to independently verify the above estimates.

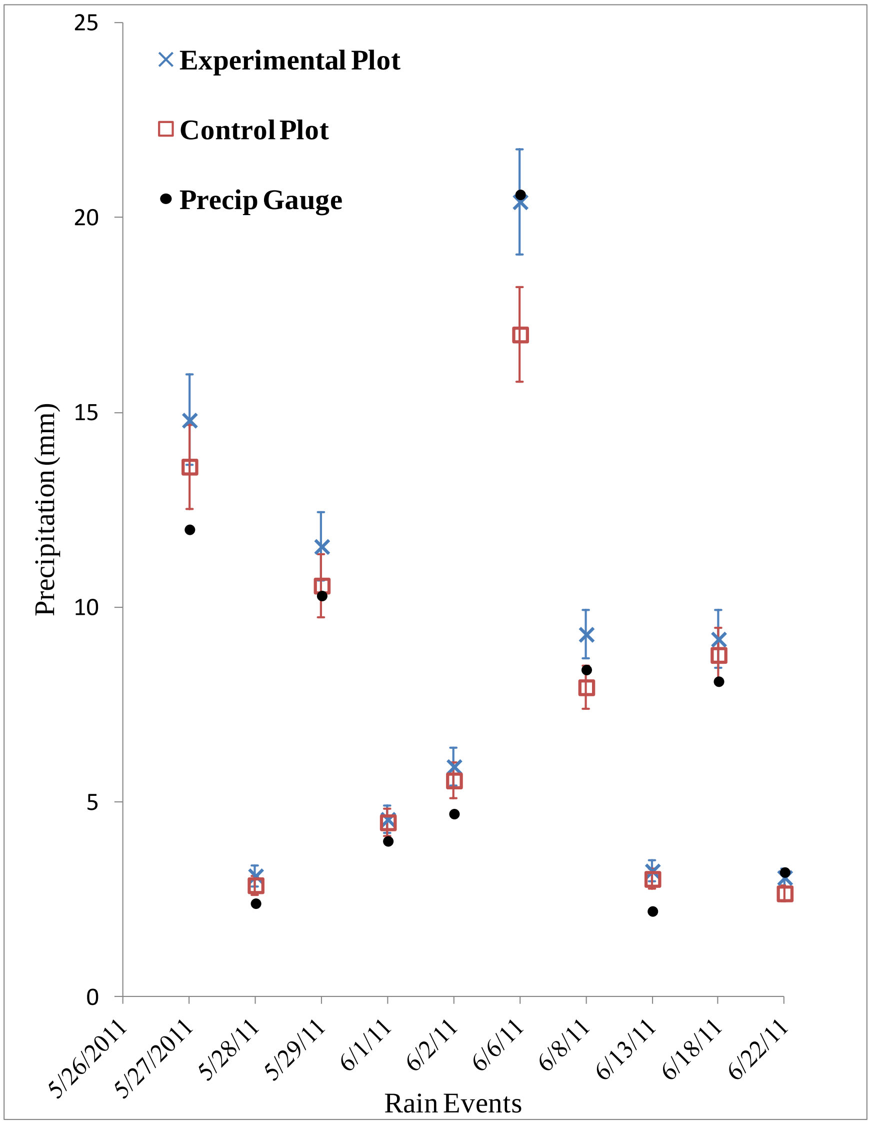

Figure 10. Paired lysimeter experiment June-July rainstorm collection efficiency comparison.

Finally, to assess the relative collection efficiencies of the two plots in a controlled environment, we applied ~6 L of water on each plot and collected it at the outlet, just before passing through the tipping buckets (to eliminate the error associated with tipping bucket volume measurements). We repeated this experiment 3 times on both plots and in all cases each plot recovered at least 95% of the applied water (Table 2), indicating that the plots at the paired lysimeter experiment have high and comparable collection efficiencies.

Table 3. Paired lysimeter experiment collection efficiency data

Plot	Applied Volume (L)	Recovered Volume (L)	% Recovered
Experimental	6.3	6	95
Experimental	6.4	6.1	95
Experimental	6.5	6.2	95
Control	5.8	5.6	97
Control	6.3	6	95
Control	6.3	6	95

4.2 Flowpath Analysis Results

4.2.1 Geometric Analysis Results

The results of the geometric analysis (Table 4) indicate that during most events, at minimum, laterally transported water was sourced between .6 and 2.8 m upslope of the collection plot. Significantly, this represents a minimum estimate of contributing length because implicit in the analysis is that all additional water collected by the experimental lysimeter (V_2 in this analysis) is sourced from a snow cube of length x_2, width y_2, and depth z_2 (Figure 6).

Table 4. Summary of paired lysimeter experiment geometric analysis

Lat Flow Start	Lat Flow End	Exp Vol (m3) Vt	Control Vol (m3) V1	Min Contrib Length (m) x2
12/11/10 22:45	12/12/10 17:30	0.085	0.036	2.8
12/14/10 6:00	12/14/10 16:15	0.159	0.068	2.6
1/16/11 0:45	1/17/11 12:00	0.605	0.293	2.1
3/9/11 13:00	3/11/11 13:45	0.135	0.065	2.2
3/13/11 16:00	3/14/11 9:45	0.118	0.078	1.0
3/15/11 11:30	3/16/11 11:15	0.229	0.156	0.9
3/30/11 2:30	3/31/11 18:30	0.441	0.290	1.0
4/1/11 12:00	4/2/11 18:15	0.159	0.121	0.6

4.2.2 Visual and Rare Earth Element Tracer Comparison Results

As expected, the snowpack in the Dry Creek Experimental Watershed exhibits extremely low (.02-.28 ppb) natural samarium concentrations (Table 5). Therefore, due to the high concentrations of applied samarium (~2000 ppm), it is appropriate to assume a negligible background level for the purpose of this study.

Table 5. Average "clean snow" samarium concentrations

Date/Location Sampled	n	Sm ppb (avg)
3/4/2011 -- Treeline	8	0.083
3/31/2011 -- Bogus	8	0.284
3/13/2011 -- Treeline	5	0.103
4/15/2011 -- Bogus	33	0.061
5/6/2011 -- LDPN	19	0.024

The results of the tracer comparison are shown in Figure 11. Figure 11a shows raw, uninterpolated concentration data and Figure 11b shows the results of linear interpolation between available data points. Samarium concentrations in the snowpack were measured at levels as low as 41 ppt and as high as 6379 ppb. We observed the highest samarium concentrations approximately 4 m below the application point at 18 cm depth. Notably, we observed a spike in the samarium concentration of 268 ppb at 10 m below the application line of 268ppb – several orders of magnitude higher than the background snow values reported in Table 5.

The results of this experiment indicate that all three tracers behave similarly. Notably, samarium was detected at levels well above background 10 m downslope from the application point and likely traveled farther downslope than 10 m (samples were not taken beyond 10 m downslope). The visual tracers Rhodamine WT and Brilliant Blue were detected approximately 15 m downslope from the application point. All three tracers were generally concentrated at subtle storm boundaries located at approximately 7, 15, and 20 cm from the surface (Figure 11). The only notable deviation from this behavior was observed between 5 and 9 m downslope where the samarium only traveled in the near surface layers of the snowpack and was not measured at the 10 and 15 cm depths (Figure 11). This behavior is likely due to the heterogeneities inherent in snowmelt processes coupled with the fact that our transect based sampling scheme allowed us to sample only a small portion of the snowpack through which the samarium may have been traveling (i.e., we may have ‘missed’ the samarium signal).

Interestingly, the visual dye and the REE tracers were not observed in high concentrations below a fine to coarse grain-size transition located at approximately 25 cm. This observation is consistent with previous work (Peitzsch, 2009; Waldner *et al.*, 2004; Wankiewicz, 1979) that has emphasized the importance of capillary barriers in routing meltwater through snow.

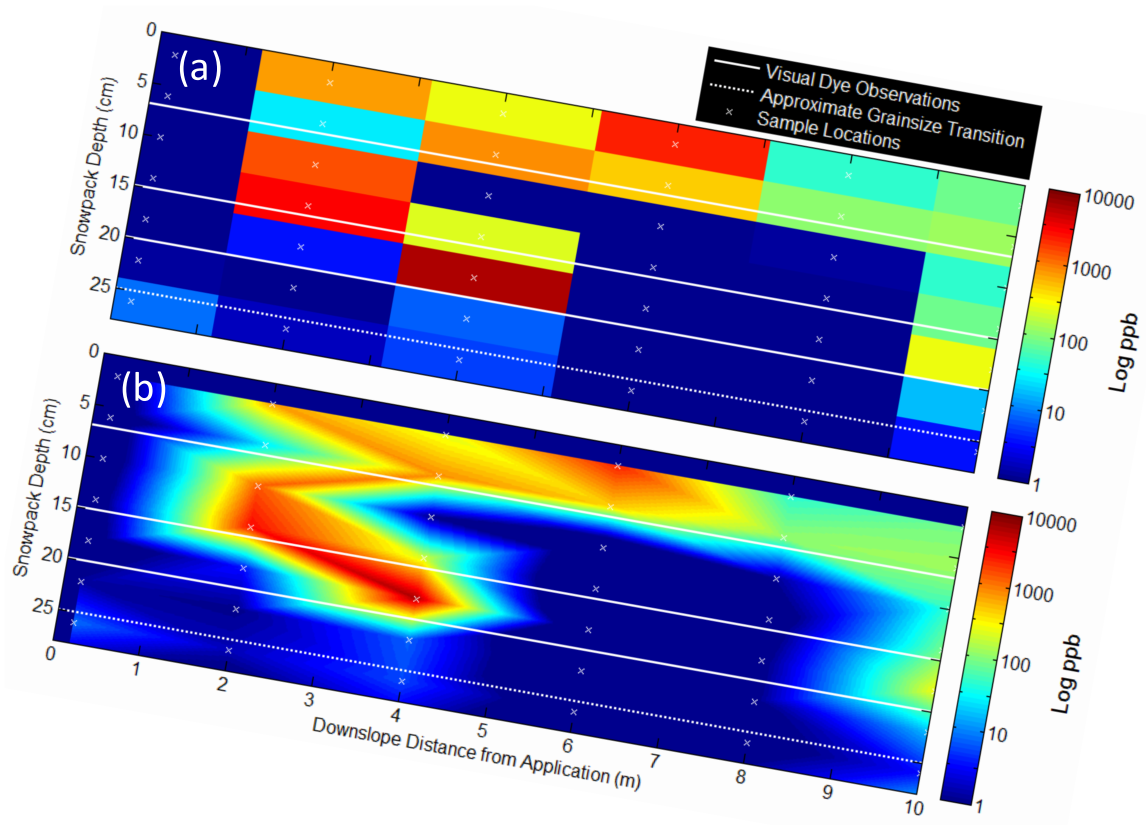

Figure 11. Sampled (a) and interpolated (b) samarium concentrations 24 hours after application. Note that the visual dye tracers and the samarium follow similar flow pathways in the snowpack and that the fine to coarse grain-size transition located at about 25 cm appears to be an effective barrier to vertical infiltration.

4.3 Tracer Race Results

Following our application of Rhodamine WT to the snow surface on March 12th, we observed significant visible evidence of down-slope water movement through the near surface layers of the snowpack. By March 14th, the Rhodamine WT had traveled at least 5-6 m downslope from the application point (Figure 7) and by March 17th, the Rhodamine WT infiltrated into the snowpack and was no longer visible on the hillslope.

Figure 12 shows a summary of the tracer race results. From March 12th to the middle of May, Rhodamine WT in the stream was recorded at levels between 0 and 30 ppb, and chloride was recorded between .8 and 1.5 ppm. The first measurable increase in the Rhodamine WT signal was observed just four days after application, on March 16th. The next major pulse of Rhodamine WT that was measured in the stream occurred on May 17th (nearly one month after initial application). Note that this peak coincided with a precipitation event that resulted in the rapid accumulation and melt of about 20 cm of snow. Prior to this snowfall event, there was no snow at the Treeline Catchment and the stream channel was nearing spring baseflow levels. Rhodamine WT concentrations next spiked at the end of May and again at the beginning of June. Less than 1% of the total mass of Rhodamine WT applied to the hillslope was recovered in the stream over the course of this study. In contrast to the highly variable Rhodamine WT concentrations, chloride concentrations showed minimal fluctuation and stayed at approximately 1 ppm for the duration of the experiment.

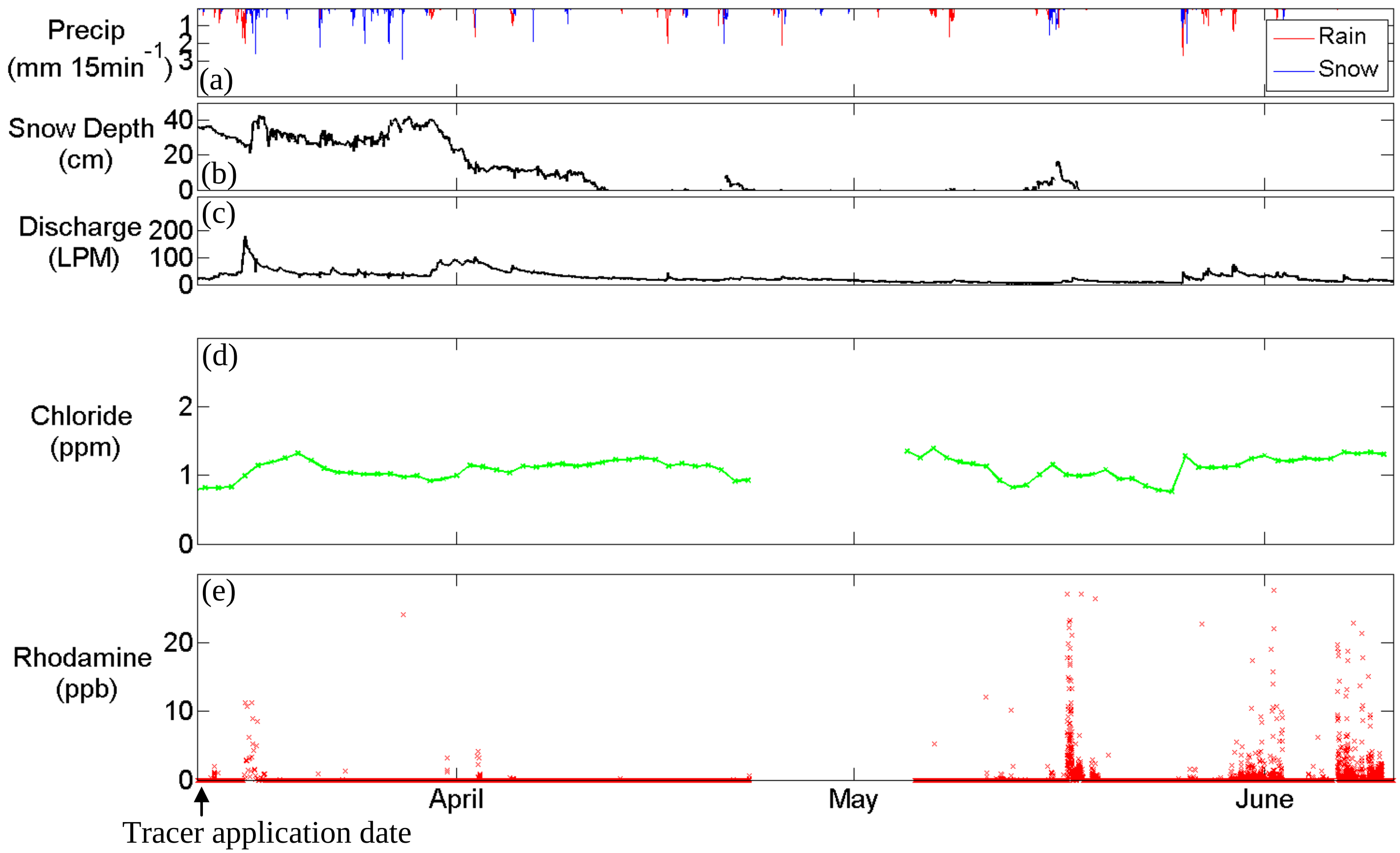

Figure 12. Summary of 2011 "tracer race" data. (a) Shows snow depth and precipitation phase/intensity for the duration of the study. (b) Shows snow depth in the Treeline Catchment. (c) Shows discharge (LPM) at the Treeline weir. (d) Depicts daily median chloride concentrations (ppm) measured in the stream channel. (e) Shows in-stream Rhodamine WT concentrations. Rhodamine WT and Chloride concentrations were measured using a continually deployed Hach Hydroprobe that recorded measurements at least every 5 minutes. The late April-early May data gap was due to instrument malfunction.

5 DISCUSSION

The goal of this study was to investigate the hydrologic significance of lateral water flow through snow during ROS and spring melt. This objective was approached by measuring lateral water flux with the paired lysimeter experiment and by comparing relative transit times of separate tracers through snow and soil. The following discusses the results of our investigation and examines the role of lateral water flow through snow in the context of stream flow generation.

5.1 Lateral Flow during Rain on Snow

The details of the snow season discussed herein introduce difficulties in assessing the importance of lateral flow through snow during *non*-rain events because *all* melt and lateral flow measured by the lysimeters corresponded with some degree of rain (Table 1). We used the ratio of lysimeter outflow depth to precipitation depth as a rough index to describe the relative importance of rain for each of the eight melt and lateral flow events (Table 1). This analysis did not reveal clear relationships between rain-dominated lateral flow events and non rain-dominated lateral flow events. Despite this, it is noteworthy that 34% of the total lateral flow measured by the paired lysimeter experiment occurred during one high-intensity ROS event in mid-January. While we speculate that lateral flow through snow is enhanced during ROS, it remains a topic of discussion whether the high volume of lateral flow observed during the mid-January event was a product of rain water moving rapidly through the snowpack, or simply high volumes of snowmelt associated with the event. Additional data documenting lateral flow volumes during non-rain events is necessary to further evaluate this issue.

5.2 Overland Flow Pathways

The results from the paired lysimeters demonstrate the importance of an above ground, downslope flux of water during spring melt and ROS (Figure 3e-f). Additionally, the results from the overland flow collector (Figure 2 and 3f) indicate the occurrence of flow either in the bottom 11 cm of the snowpack or along the ground surface. The similarity in results between the overland flow collector and the paired lysimeters, particularly during the first two melt events of the season, are striking. Because the overland flow plot will only accept water movement through the bottom few centimeters of the snowpack, similar to Ohara et al. (2011), we interpret that the majority of the lateral flow collected by the paired lysimeter experiment traveled in a similar part of the snowpack.

Interestingly, after the first two melt events in December and January, we observed a divergence between apparent overland flow (collected by the overland flow plot) and lateral flow through snow (Figure 3f). The design of the collection plots may help to explain this behavior. Recall that prior to March 6th, the control plot only blocked flow in the bottom 20 cm of the snowpack and that after March 6th the control plot was completely blocked and no upslope contributions were possible. It is possible that the difference between the two measurements after March 6th is due to lateral flow through snow above the 20 cm barrier that would not have been recorded prior to the installation of the one meter tall blockages.

Visual tracer tests by Whitson (2009) also showed substantial downslope movement of dye in the base of the snowpack. Further, this interpretation is consistent with our observation of a persistent basal ice layer on the North facing slope in the Treeline Catchment that may have formed following the mid-January ROS event.

The saturated soil conductivity at the Treeline Catchment (measured *in situ* by Gribb et al. (2009)) is 288 mm hr^{-1} in the top 24 cm of the soil profile and 133 mm hr^{-1} from 24 to 53 cm. The maximum melt rate measured by the lysimeters was 18 mm hr^{-1}. By definition, infiltration excess overland flow will only occur when water input exceeds the saturated conductivity (Dingman, 1994). Because water input was at least an order of magnitude lower than saturated conductivity throughout the melt season, it is unlikely that Hortonian overland flow was ever a dominant runoff generation process in the Treeline Catchment during the 2010-2011 snow season.

While we suspect that lateral flow at the base of the snowpack is the dominant *over land* downslope routing mechanism in the Treeline Catchment, small volumes of Hortonian overland flow have been measured in the absence of a snowpack. On 10/4/11 – 10/7/11, for example, 41 mm of rain fell onto bare soil over a 75-hour period in the Treeline Catchment and 2.5 L m^{-1} of overland flow was documented. It is noteworthy that the magnitude of overland flow measured during this event is considerably less than the magnitude of overland flow measured in the presence of a snowpack (Figure 3e-f), suggesting that snowpacks significantly enhance above ground water transport, regardless of pathway (i.e., soil surface or base of the snowpack).

5.3 Lateral Flow through Snow and Runoff Generation

The question of lateral flow through snow source area remains a topic of interest and discussion, in large part because of the difficulty inherent in such estimates. Previous work by Whitson (2009) showed that water delivery to the stream channel may occur from as far upslope as 24.3 m. Further, the results of the tracer comparison experiment (Figure 9) suggested that the altered albedo imposed by colored dye on snow has a minimal impact on melt dynamics in these studies. The results of our geometric analysis (Equation 3) indicate that during the 2010-2011 snow season, water traveled laterally through the snowpack a minimum distance of .6 to 2.8 m in the Treeline Catchment (Table 3). Significantly, these estimates of upslope contributing length (x_2) assume that *all* additional water collected by the experimental lysimeter (V_2 in this analysis) is sourced from a snow cube of length x_2, width y_2, and depth z_2. This is an unrealistic assumption because numerous dye studies (e.g., Whitson, 2009) have shown that lateral water movement through snow occurs in thin layers at conductivity barriers within the snowpack. Despite this, the analysis serves as a method for understanding the minimum contributing area necessary to explain the laterally transported water collected by the experimental lysimeter.

While the length scales involved with lateral flow through snow are significant, one of the general extensions of our results is that during ROS and spring melt, a certain amount of water is routed downslope and *directly* delivered to the stream channel without ever traveling through the soil profile. To estimate the direct contribution to the stream channel, we used the following equation:

$$\text{Direct Contribution} = \text{LF}^* \ \text{CL}^*2 \qquad (4)$$

where LF is lateral flow ($m^3\ m^{-1}$), CL is channel network length (250 m), and 2 is the number of contributing slopes to the stream channel. The implicit assumption here is that the lateral flow values calculated from the paired lysimeter experiment are representative of the entire hillslope on both aspects in the Treeline Catchment. Also note that this calculation does not account for the position of the lysimeters on the hillslope. If lateral flow occurs on a length scale longer than the distance from the lysimeters to the ridge (~25 m), our calculations will represent a lower bound on direct contribution to the Treeline Catchment stream.

Figure 13 shows the results of this analysis by comparing the estimated contribution from lateral flow through snow with Treeline Catchment discharge for the duration of the snowmelt season. The January 15-17 ROS event presented an ideal opportunity to calculate the percentage of total discharge attributable to direct lateral flow channel delivery for an individual snowmelt event because the hydrograph rise and fall came as one event, making it easy to delineate baseflow conditions. Further, during this event the snow coverage in the Treeline Catchment was fairly uniform, thus helping to validate the assumption of equal contribution from both aspects. For this event, we used Equation 4 to calculate that lateral flow may have accounted for as much as 12% of total discharge. This estimate may help to explain the results of a hydrograph separation study performed in the Treeline Catchment (Yenko, 2003) that indicated “new water” contributions to discharge as high as 59-65% of total runoff during snowmelt. This result is higher than commonly reported and we suggest that these values may be due, in part, to direct contribution from lateral water flow through the snowpack. For reference, we also calculated direct channel precipitation during this event, assuming a channel width of .3 m, and found that it accounted for less than 1% of total discharge (Figure 13).

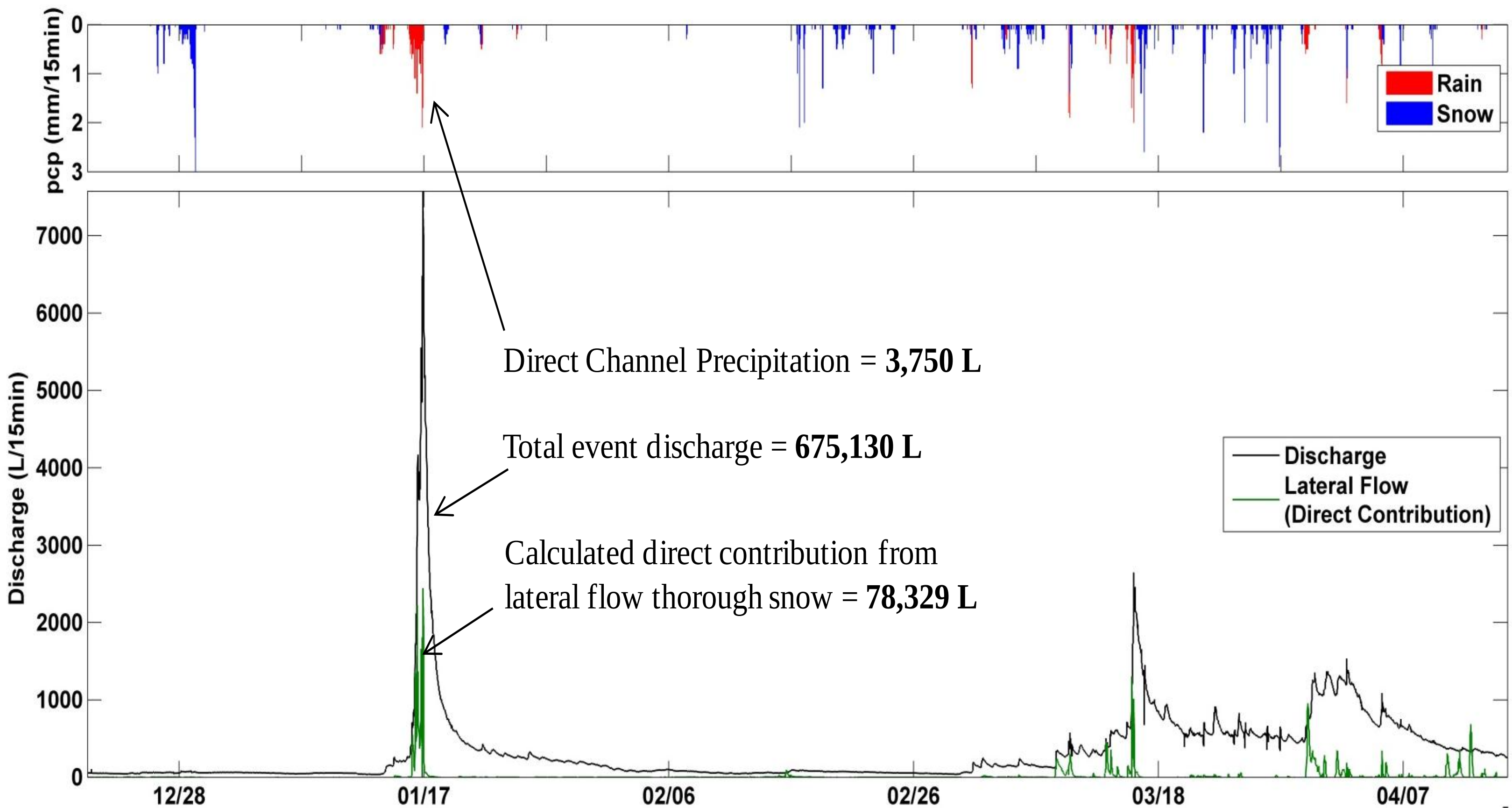

Figure 13. Direct contribution to Treeline Catchment discharge

Unfortunately, estimates of the percentage of total discharge associated with direct lateral flow contributions from other *individual* snowmelt events are impractical because unlike the Jan 15-17th ROS event, for the remainder of the snow season, it is difficult to accurately estimate baseflow conditions and attribute hydrograph rises to individual melt/lateral flow events. Despite challenges associated with determining the percentage of direct channel delivery, it is noteworthy that throughout the melt season there is very clear agreement in timing between estimated contributions from lateral flow through snow and peaks in discharge (Figure 11). This is particularly significant because the timing of lateral flow peaks are insensitive to the assumptions noted above (i.e., uniform contributions from both aspects over the entire length of the basin). One hypothesis to explain the close correlation between discharge peaks and lateral flow peaks is that contributions laterally through the snowpack directly to the stream channel are not subject to the typical lags associated with snowmelt-discharge relationships.

It is possible that lateral flow through snow is not the primary reason for the agreement between the two measurements. While this thesis focuses on the importance of lateral flow through snow, the vertical component of melt is likely dominant for much of the snowmelt season. McNamara et al. (2005) emphasized the importance of pressure-wave translation for streamflow generation in the Treeline Catchment. Therefore, it follows that vertical water inputs will yield rapid discharge response due to the likelihood that there is hydrologic connectivity across the hillslope during melt events. This interpretation is supported by Figure 3c, which shows consistent agreement between snowmelt events, increases in near-surface soil moisture, and peaks in discharge.

While the estimated 12% direct contribution during the January ROS event *is* significant, note that this percentage is only a measure of the direct contribution to the stream and does not account for total downslope water flux. We suggest that in addition to direct channel delivery, a significant amount of water is transported to near-stream locations, whereby it more easily contributes to discharge.

Evidence for the importance of this process is demonstrated in the results of the tracer race (Figure 10). In the days immediately following the application of Rhodamine WT to the snow surface, we observed the tracer traveling ~5-6 m downslope in the near-surface layers of the snowpack. We also measured small but measurable increases of Rhodamine WT concentrations in the stream, suggesting that the tracer was directly transmitted to the stream channel through the snowpack. After this initial evidence of downslope Rhodamine WT transport through the snowpack, no increases in Rhodamine WT concentrations were observed until well after the snowpack had melted and subsequently delivered the Rhodamine WT that was stored in the snowpack to the soil. Beginning in the middle of May, a portion of the Rhodamine WT that was stored in the soil was mobilized by the accumulation and immediate melt of ~20 cm of snow. Over the next several weeks, additional Rhodamine WT was mobilized by precipitation events and delivered from the soil to the stream channel–an unexpected result due to the non-conservative nature of the tracer (e.g., Sabatini and Austin, 1991).

Significantly, for the duration of our stream chemistry monitoring effort, we observed no significant change in chloride concentrations in the stream. To ensure that this result was not attributable to chloride dilution on the hillslope, Hetrick (personal communication) performed regular resistivity surveys for the duration of the study to image the chloride plume. His results showed that the applied chloride traveled only ~4 m downslope over the duration of the experiment, and therefore never reached the stream channel.

We interpret these results to be evidence for the importance of down-slope transport of water through the snowpack irrespective of direct channel delivery. We suggest that Rhodamine WT concentrations increased and chloride concentrations stayed constant because the Rhodamine WT was rapidly transported several meters downslope prior to end of the permanent snowpack at the Treeline Catchment, thus making it *easier* for the tracer to reach the stream channel. Because the chloride tracer did not have the benefit of rapid downslope transport through the snowpack, it was limited to slower pathways through the soil and failed to reach the stream channel during the duration of our study.

This interpretation (conceptually diagrammed in Figure 14) may also help to explain the observation by Williams et al. (2009), wherein it was observed that near surface soil moisture content tends to increase downslope in the Treeline Catchment despite the lack of evidence supporting lateral flow in near-surface soils at the same site (Makram-Morgos, 2006). It should be noted, however, that recent work by Smith et al. (2011) downplayed the importance of snowmelt as a control on the spatial variability of soil moisture in Dry Creek. This conclusion was based on the observation that low soil moisture storage capacity in Dry Creek causes soils to reach field capacity early in the winter. Smith et al. (2011) point out that additional water inputs from snowmelt after field capacity is attained contributes only to deep drainage. Despite the lack of clarity regarding the relationship between lateral flow in snow and soil moisture in the Dry

Creek Experimental Watershed, we suggest that the phenomenon has the potential to influence the spatial variability of soil moisture in snow-dominated catchments.

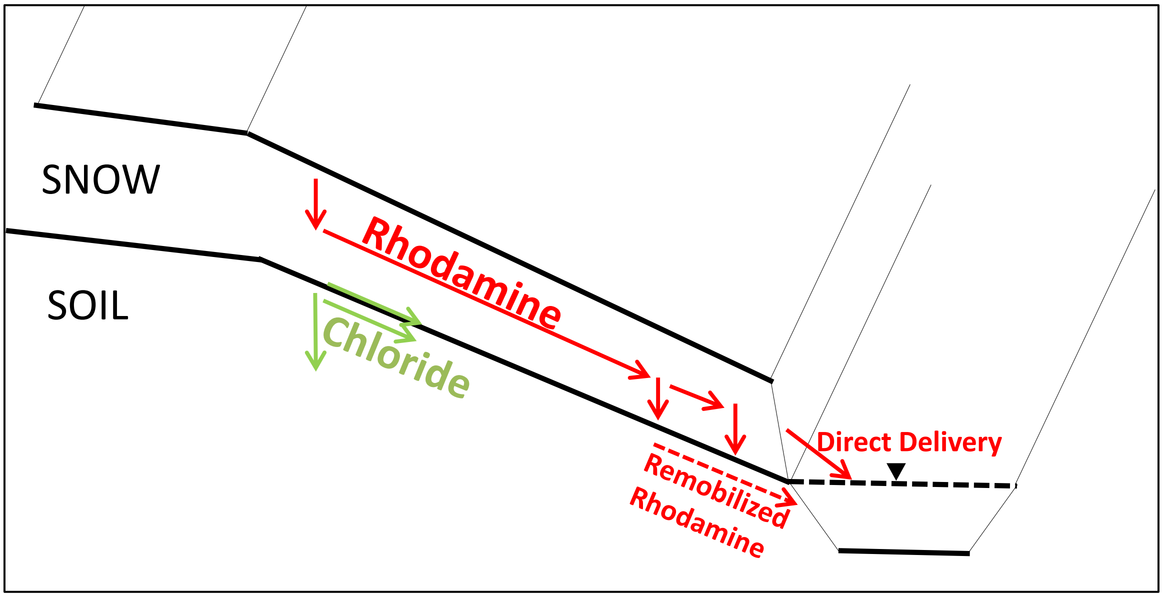

Figure 14. Conceptual model to explain the results of the "tracer race".

6 CONCLUSIONS

The goal of this study was to investigate the hydrologic significance of lateral water redistribution in a seasonal snowpack by both physically measuring the downslope flux of water through the snowpack and comparing the relative transit times of water through the snowpack and the soil. The primary findings of our study are as follows:

- Over the duration of the snowmelt season, a snowmelt lysimeter that was unblocked from upslope inputs collected ~47% more water than an identical lysimeter that was blocked from upslope inputs. These results suggest that lateral flow through snow may be a hydrologically relevant process.
- During a major mid-winter rain on snow event, lateral flow through the snowpack may have directly contributed up to 12% of discharge recorded in a small catchment located just outside of Boise, Idaho.
- The timing and magnitude of lateral flow recorded with the paired lysimeters was in close agreement with the timing and magnitude of an independent measurement of apparent overland flow at the same research site. Due to the coarse-grained, highly conductive granitic soils in our study watershed, we do not expect traditional Hortonian overland flow to be a dominant water pathway. Rather, we believe that the majority of water recorded by the overland flow collector was routed downslope in the bottom few centimeters of the snowpack.

- The results of a snow vs. soil “tracer race” indicate that snow can serve as a rapid downslope delivery mechanism relative to soil.

We acknowledge that the extension of our interpretation that lateral flow through, or at the base of, the snowpack is hydrologically significant is challenging due to our fairly limited field measurements and the extreme spatial heterogeneity of snow cover and snow stratigraphy within a single catchment, let alone across different hydroclimatic regions. Questions remain regarding the importance that snowpack depth and rain-on-snow have on lateral flow through snow. The results presented in this thesis show that a hydrologically significant volume of lateral flow is transmitted through an unstratified, shallow snowpack located in a transitional rain-snow environment. It is possible that the prevalence of rain-on-snow events at our study site is closely linked to our observations of lateral flow. However, because all recorded melt events were accompanied by some rain, it is difficult to accurately assess this claim without additional data. Deep snowpacks located in high elevations typically exhibit complex stratigraphy that might serve to more efficiently route water laterally downslope. However, because higher elevation snowpacks are less susceptible to rain-on-snow, it is *also* possible that lateral flow through snow is less prevalent in these environments. Additional lateral flux measurements in high elevation, stratigraphically complex snowpacks are needed to resolve these remaining questions further.

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