Dear Editor and Reviewers,

We would like to thank you for spending the time that you did in reviewing our revised manuscript. We appreciate the constructive comments that were given and believe that incorporation of these comments to our revisions has greatly improved the quality of the manuscript. We have addressed every comment. Please find below a restatement of each comment followed by our response in green text. We have also quoted the lines of the revised text to aid in reviewing our response. Following these comments is a copy of the revised manuscript with tracked changes. Again, thank you.

10 Sincerely,

5

Ryan Webb

- 15 Editor Decision: Reconsider after major revisions (10 Oct 2017) by Valentina Radic Comments to the Author: Dear authors,
- Your revised manuscript has by now been reviewed by both original reviewers. They both acknowledge that the quality of the manuscript has improved, however, they provided more comments that need to be addressed. Please find attached their reviews below.

Please address these comments point by point in your response letter and submit the responses together with your re-revised manuscript.

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Thank you, Valentina

Review#1

In revised manuscript, it was recognized that most of responses and revisions for each comments were conducted appropriately.

Addition of snow depth in Figure 4 provided clear information that SWE increased despite snow depth decreased. I understand bulk snow density increased considerably at NT. As far as my interpretation

35 of Fig 4, bulk density at NT increased from 200 to 400 kg/m3 or so from first measurement to second one. Now it is understandable that lateral flow in the snowpack seems significant effect.

I felt that additional description is necessary about the estimation of ratio of lateral flow. As a response of quantitative analysis, ratio of lateral flow was estimated using calculated snowmelt

40 amount. I think this method is appropriate. On the other hand, I felt many points are unclear about this estimation. For example, how was the ratio calculated to 4%? How long period was used to estimate the value 4% (for whole winter or specific period)? Was there a difference of ratio of lateral flow between north and south facing slope? Adding these descriptions provide more available information.

45

Thank you for taking the time to review our manuscript a second time.

The ratio of 4% was calculated through contributing areas to the locations of the snow pits. We used the elevation DEM to make a approximation of this contributing area for the observation locations. As for the difference with the south facing slope, this calculation was not conducted. The main reason that this was not done is that little evidence exists that lateral flow occurred on the south facing slope and any lateral flow that did occur would drain from the snowpack rather quickly due to the soil properties of that hill slope inhibiting our ability to observe these changes in SWE. Below are the text quotes of the new manuscript.

55

P11 L16-18

"Using the 10 m DEM we estimated average contributing areas for the snow pit locations on the north facing slope. We then used the changes in SWE and observed precipitation to estimate the contribution of lateral flow for the two week periods between observations.

Review#2

General comment:

- 5 The Introduction and Methods sections were mainly kept unchanged. The Results and Discussion parts were partially modified. The additional data (density profile) presented in the Results part don't really bring any added value. The discussion is still redundant and several inconsistencies are still present. I would suggest a much more in-depth modification of the paper.
- 10 Thank you for taking the time to review our manuscript again. We have revised the text taking careful consideration of your comments and believe it has improved the quality of the paper. The reason that the density profiles were added is because it was a point made from both reviewers of the original manuscript; though we agree that little is added from the profile other than the context of snow layering to compare the years. It is pretty standard for snow studies and readers may be expecting to
- 15 see it, so we chose to leave it in.

We have also revised the text to reduce redundancy beyond only your specific comments, please see our responses below.

20 Detailed comments:

P3 L10 Not sure Webb et al. is appropriate at that place.

More generally, this reference hasn't been changed throughout the text (mix between Webb et al. in review and Webb et al., 2017).

- We believe that it is appropriate and the title of the paper in the references ("The The Presence of Hydraulic Barriers in Layered Snowpacks: TOUGH2 Simulations and Diversion Length Estimates") should help show how it is applicable here. We added the Avanzi reference to ensure that it was not only an "in review" paper that supported the claim. Unfortunately that journal took 1 year for the first round of reviews so it is still in review. We believe it will be published in the near future. Furthermore, the Webb et al., in review and Webb, 2017 are two separate references.
- 30
- Webb, R. W.: Using Ground Penetrating Radar to Assess the Variability of Snow Water Equivalent and Melt in a Mixed Canopy Forest, Northern Colorado, Frontiers of Earth Science, doi: 10.1007/s11707-017-0645-0, 2017.
- 35 Webb, R. W., Fassnacht, S. R., Gooseff, M. N., and Webb, S. W.: The Presence of Hydraulic Barriers in Layered Snowpacks: TOUGH2 Simulations and Diversion Length Estimates, Transport in Porous Media, in review.

P6 L8-11 Why are you not mentioning 2014 in your analysis?

40 The reason is that these statements are only discussing the range of earliest to latest peak dates. We have added text to clarify this point so readers are not confused.

P6 L8-11

"Peak SWE timing ranged from the earliest on March 9 in 2015, preceding first survey by nearly one
 month, to the latest on April 25 in 2013, 19 days after the first survey (Fig. 2a). The number of days
 from peak SWE to no snow recorded at the SNOTEL station ranged from the fewest in 2013 of 22 days
 to the most in 2015 of 52 days..."

P6 L11-13 What fraction of precipitation was recorded as snow/rain (based on temperature measurements)? This would be interesting to have an estimate and put it in relation with the SWE increase observed in Fig 4.
 Agreed. Please see revised fig. 4. below that now includes a red component of the precipitation bar that represents precipitation that fell when air temperature (T_{air}) was greater than 1°C.



- P6 L25-33 First, I would suggest a step chart instead of a line for the density graph. This would help
 the reading of the graph (and maybe highlighting relevant features). This paragraph sounds highly
 hypothetical ("that display indicators of melt-freeze crusts...", "likely as the result of melt-freeze
 cycles") given that the measured densities (Fig. 3) are not that high. In addition, I don't really
 understand the added value of those observations with regard to the main message. The profiles were
 done near the SNOTEL site, closer to the south aspect slope and should be homogenous (following
- 10 your argumentation). Could you please clarify this point? We agree with your first point. The figure is now a step graph. I do not follow why the profiles would be homogenous. Regardless of if lateral flow is occurring in snow there will still be metamorphism and compaction processes that create a stratified snowpack. The new figure is shown here.



25

P7 L5-8 As mentioned before, you could compare the change in SWE with the new precipitation and if possible, estimate which part of it due new snow.

20 This comparison is conducted in the energy budget analysis in the discussion and have been revised to clarify that this was being done.

P11 L17-18

"We then used the changes in SWE and observed precipitation to estimate the contribution of lateral flow for the two week periods between observations.

P7 L20-21 How can you affirm that ice veins are continuous? Please clarify.

We used the term "appear" because we can not affirm that they are continuous for the entire slope, we have added language to clarify.

The text now reads: P7 L21-22 "...appeared to be continuous, though continuity was only confirmed 5 for three to four meters based on excavation."

P7 L32 How do you define that the soil is super-saturated? We define this by observed ponding on the surface, we have now added this wording to be sure it is understood clarify.

P7 L 32-33"...super-saturated during a single survey on April 19, 2014 (resulting in the 85% VWC and surface ponding, Fig. 4bii)"

- P8 L31-33 The difference seems much smaller in 2014 (figure 6) between VWC at 5cm an 12cm. How 15 do you explain this? Wouldn't be relevant to show the entire year 2014? It may be a result of the mid-winter installation. We have also added wording to further explain this, though this was mentioned in the methods already to explain why the entire 2014 year was not shown. We have also edited the text throughout to highlight the difference at 20 cm depth with less 20
- emphasis on the 12.5 cm VWC.

P5 L29-31: "Installation in December 2013 required disturbing the snowpack and soil, thus the snowpack and soil moisture were allowed to return to near undisturbed conditions after installation and data prior to March 15, 2014 was not included in analysis."

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P8 L 32-33: "This is more pronounced in 2015 where the 2014 season may have been impacted by the mid-winter installation of the sensors"

P9 L12-13 Can you really compare VWC values from a flat and sloped terrain like this? There are of 30 course differences in soil types and drainage properties (induced by the slope)! We agree. However, the point of this paper is that drainage is different on the slopes and the snowpack is part of the sloped drainage dynamics. The combination of all components including the

soil, slope, and snowpack are what create the observations and is the main point of our manuscript. We discuss all of these factors in great detail in the discussion, though the combined effects are 35 summarized in the lines.

~P12 | 30-32

"...it is important to consider the variable flowpaths that develop based on factors such as slope, aspect, soil parameters, and snowpack characteristics to move beyond single point measurements and one-dimensional assumptions."

P9 L20-23 From what you say (P7 L23: These ice "veins" were not observed in 2015) and show in Figure 6, these two observations (ice veins and VWC values) were not done the same year. Your sentence suppose the opposite and is misleading.

We agree and see your point. We were not intending to be misleading, the text has been revised in to 45 be more clear that there was less infiltration to 20 cm depth in 2014 during the early meltseason when the ice veins were observed.

P9 L21-23

50with more infiltration wetting the soils at 20 cm depth on the flat aspect and lesser wetting at this depth on the north aspect in the early meltseason (Fig. 6b) where observations of ice "veins" and saturated layers of snow were made at the SSI (Fig. 5)."

P9 L25-26 Your statement is clearly not always correct (see in figure 4 for example aii) ST vs NH, aiv) NL or NH vs ST avi) NH vs ST). Please be more cautious. 55

Thank you for pointing this out, it was intended to pertain to locations on the slopes and not at the toes (SM, NL, and NH). You were comparing the ST location that was not intended as part of this statement. We agree that it was previously worded in a way that this was not clear and have revised it.

P9 L25-26

"...north aspect soils often having similar and/or higher water contents than south aspect soils, both with and without the presence of a snowpack (Fig. 4, SM vs. NL and NH)."

5

P9 L26-27 This sentence doesn't bring any interesting information. Consider removing it! We agree. The sentence has been removed.

P9 L31-36 How do you explain the negative correlation? Try to clarify that part of the discussion (P9 L31 to P10 L6).

This negative correlation means that lower peak SWE (during first survey) correlates to higher VWC later in the season. We have reworded the sentences to be more clear in our explanation.

P9 L32-36

15 "This negative correlation indicates that locations with lower peak SWE (During the first survey of the season) tend to have greater VWC at the later surveys. This is the result of the shallower snowpacks during the first survey being near the bottom of the slopes and in the flat terrain influenced by canopy interception (Fig. 1a) and the following melt flows downslope at the SSI towards these locations increasing both SWE and near surface VWC during the following surveys"

20

P10 L7-11 As mentioned above, you are misleading the reader by putting together observations from different years. Increase in SWE and ice veins was observed in 2013 and 2014, reduced infiltration in 2015 mostly.

We were not intending to be misleading and have added wording to be more clear. The reduced

25 infiltration to 20 cm depth does also occur in 2014. Particularly during the early meltseason when the ice veins were observed.

P10 L7-8

"...the frozen "ice veins" observed in 2013 and 2014 early melt seasons (Fig. 5), less infiltration to 20 cm depth on the slope (Fig. 6),..."

P10 L16 Not sure Webb et al. is appropriate here.

We believe that the title should speak to how it relates, though it will be more clear in its appropriateness when it is published. This is

Webb, R. W., Fassnacht, S. R., Gooseff, M. N., and Webb, S. W.: The Presence of Hydraulic Barriers in Layered Snowpacks: TOUGH2 Simulations and Diversion Length Estimates, Transport in Porous Media, in review.

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P10 L16-17 How can you justify from figure 4 that not ice veins were observed on south facing slope? We see your point and have removed the reference to that figure. However, the evidence for lateral flow extends beyond ice veins to the increases in SWE (Fig. 4) and saturated layers within the snowpack that were not observed on south facing slope.

45

P10 L24-25 Why slower melt rates would induce lateral flow in the snowpack? Please clarify! This is a result of the physics of unsaturated flow. We have added a sentence to clarify the effects of slope and infiltration rate, and offer the appropriate references to refer the readers to the appropriate literature to learn more details about these physics. We feel that going into too much detail concerning

50 the physics of unsaturated flow would make the article longer than necessary. These processes are the primary focus of the entire paper Webb et al., in review.

~P10 L19-21

"When capillary barriers occur, the diversion length will be controlled by the hydraulic properties of the media, slope of the interface (steeper slope increases diversion length), and infiltration rate (slower infiltration rate increases diversion length) (Webb, 1997; Webb et al., in review)."

The paragraph P10 L29 to P11 L7 is mainly a repetition of elements already mentioned in paragraph (P10 L7 to L28). Revise this part of the discussion and remove redundancy. We agree and have compiled these two paragraphs into a single paragraph.

5

P10 L6-30:

"Meltwater flowing downslope near the SSI on the north aspect hillslope is shown by the increases in SWE at locations on and at the toe of the hillslope (Fig. 4), the frozen "ice veins" observed in 2013 and 2014 early meltseasons (Fig. 5), less infiltration to 20 cm depth on the slope (Fig. 6), similarities

- 10 in soil moisture between snowmelt and overland flow rain events, and the observations of snow density and wetness increasing with depth downslope in each north aspect snow pit. For the south aspect slope, the increases in SWE at the ST locations were similar to observed precipitation in 2013 and an increase in snow depth for 2014. The south aspect slope may have meltwater flowing downslope near the SSI, though to a lesser extent than the north facing slope and less apparent. The
- 15 movement of water across layer interfaces has been shown within a snowpack (Williams et al., 2000; Liu et al., 2004; Williams et al., 2010) and at the SSI (Eiriksson et al., 2013), with evidence of the latter being observed in this study (Fig. 5). This phenomenon will depend on soil parameters, snowpack layer characteristics, slope angle, and the rate that meltwater is percolating through the snowpack. These factors will determine if an interface acts as a permeability barrier, similar to a soil
- 20 drain, or a capillary barrier (Avanzi et al., 2016; Webb, 1997; Webb et al., in review). The primary reasons for lateral flow through the snowpack on the north facing slope is a result of the slower melt rates and hydraulic conductivity of the soil. When capillary barriers occur, the diversion length will be controlled by the hydraulic properties of the media, slope of the interface (steeper slope increases diversion length), and infiltration rate (slower infiltration rate increases diversion length) (Webb,
- 25 1997; Webb et al., in review). It is also possible for lateral flow to be caused by barriers within a layered snowpack well above the SSI, though the large saturated layer of snow was observed only at the SSI in all north aspect snow pits showing this is where the bulk of the lateral flow occurs. Further testing and field experiments are necessary to quantify the influence of varying slope and soil parameters on these processes in and below a snowpack. Our study shows preferential flowpaths
- 30 during snowmelt on the north facing slope that are similar to an alpine catchment with water flowing through the snowpack downslope (Liu et al., 2004, Williams et al., 2000), during rain on snow events at lower elevation sites (Eiriksson et al., 2013), and observations in a coastal climate (Kattelmann and Dozier, 1999).. These processes can be combined into a conceptualization of the northern aspect slope having meltwater flowpaths near the SSI downslope and the southern aspect slope having more infiltration into the soil (Fig. 7)."

P11 L15-16 You are referring to the wrong figure (Figure 4c) and consider revising the sentence "displaying the increased the storage capacity".

40 Revised.

P11 L1-2

"...increase in bulk SWE by up to 250 mm (from 146 mm to 396 mm, Fig. 4aiii) displaying the increased storage capacity of a location by the porosity of the snow."

45

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P11 L20 Why are you saying that north slope can generate streamflow later in the summer (and referring to Figure 6bii)? Please clarify!

This figure shows the longer persistence of the snowpack later in the summer when there is no longer snow on the south facing slope or flat (SNOTEL). However, we agree that this may have been a confusing point and have thus removed this part of the sentence.

P11 L21-37 I am a bit skeptical that an increase of 170% in SWE can only explained by lateral flow in the snowpack. And how do you explain the increase at the toe of the south aspect slope? I would suggest that the rise of the water table is a major contributor to this change in SWE (as you mentioned of the discussion).

55 mentioned at the end of the discussion). Yes, we agree and explain that it is a contributor but increases in SWE upslope at NL where water table is not rising also confirm the lateral flow process and were used to determine the 4% calculations. South facing increases in SWE are at a location that is also increasing in depth from topographic variability so not necessarily increasing in density from lateral flow like the NT. When the south facing location does increase without a similar increase in depth it is close to the observed precipitation so difficult to separate. We have added text to clarify this difficulty at the south facing slope.

5 P11 L16-25

"Using the 10 m DEM we estimated average contributing areas for the snow pit locations on the north facing slope. We then used the changes in SWE and observed precipitation to estimate the contribution of lateral flow for the two week periods between observations. Given the observed increases in SWE on the north facing hillslope this results in a minimum of 4% of melt traveling

- 10 laterally above the SSI to produce the observed increases in SWE. The 4% is water that flows downslope above the SSI and remains in the snowpack. Therefore, the percentage may be larger when considering drainage from the snowpack after flowing laterally. Though 4% of melt flowing downslope within a snowpack is a low number it accumulates along the 250 m hillslope to increase the SWE at the toe of the slope the most. The 170% increase in SWE at NT observed in 2014 (Fig. 4) is
- 15 likely a result of both water flowing above the SSI and below it causing the water table to rise, though the increases in SWE at NL can be attributed to flow above the SSI."

P10 L10-12

"For the south aspect slope, the increases in SWE at the ST locations were similar to observed

20 precipitation in 2013 and an increase in snow depth for 2014. The south aspect slope may have meltwater flowing downslope near the SSI, though to a lesser extent than the north facing slope and less apparent."

P12 L4-7 I don't understand how you justify the different behaviors between 2015 and 2013-2014

25 (notably the link between melt and soil behavior). Just because of the shallower snowpack? Could you clarify this point please?

These lines do not relate to this, though we believe that the revised version explains our justifications. In 2015 our observation period was much after peak SWE and there was a number of rain events that created a different environment. In responding to your comments above we have clarified the reduced infiltration to 20 or double backward 2015. We have added the entropy below to

30 infiltration to 20 cm depth in both 2014 and 2015. We have also added the sentence below to recognize that we were unable to observe some of the processes in 2015 due to the early peak SWE.

P12 L25-28:

"Future hillslope scale investigations of these phenomena may benefit from larger scale runoff
 lysimeter studies similar to Eiriksson et al. (2013) and observing the entire melt season to capture peak SWE processes in low years."

P12 L26 figure 53....

Thank you for pointing this out. We have corrected it and given the revised document a solid proofread to catch any other mistakes similar to this.

P12 L28 You state: "The south aspect hillslope did not display evidence of this phenomenon". In 2013 and 2014, you observed an increase in SWE at the toe of the south facing slope (Figure 4 bi and biii). How do you explain it? I would lean towards a rise of the water table in the valley (encompassing ST F and NT sites) that would partly bias all measurements.

45 and NT sites) that would partly bias all measurements. The water table was not observed to rise up into the snowpack at the ST location. Please also see above response concerning the explanation for the rise in SWE at ST.

P10 L10-12

- ⁵⁰ "For the south aspect slope, the increases in SWE at the ST locations were similar to observed precipitation in 2013 and an increase in snow depth for 2014. The south aspect slope may have meltwater flowing downslope near the SSI, though to a lesser extent than the north facing slope and less apparent."
- 55 In Figure 2a, modify the x-axis to have a tick every month. It does have a tick every month, though the box marker covers it up for May.

Hydrologic Flowpath Development Varies by Aspect during Spring Snowmelt in Complex Subalpine Terrain

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Abstract. In many mountainous regions around the world, snow and soil moisture are key components of the hydrologic cycle. Preferential flowpaths of snowmelt water through snow have been known to occur for years with few studies observing the effect on soil moisture. In this study, statistical analysis of the topographical and

- 10 few studies observing the effect on soil moisture. In this study, statistical analysis of the topographical and hydrological controls on the spatio-temporal variability of snow water equivalent and soil moisture during snowmelt was undertaken at a subalpine forested setting with north, south, and flat aspects as a seasonally persistent snowpack melts. We investigated if evidence of preferential flowpaths in snow can be observed and the effect on soil moisture through measurements of snow water equivalent and near surface soil moisture, observing how SWE and near surface
- 15 soil moisture vary on hillslopes relative to the toes of hillslopes and flat areas. We then compared snowmelt infiltration beyond the near surface soil between flat and sloping terrain during the entire snowmelt season using soil moisture sensor profiles. This study was conducted during varying snowmelt seasons representing above normal, relatively normal, and below normal snow seasons in northern Colorado. Evidence is presented of preferential meltwater flowpaths at the snow-soil interface on the north facing slope causing increases in SWE downslope and less infiltration
- 20 into the soil at 20 cm depth; less association is observed in the near surface soil moisture (top 7 cm). We present a conceptualization of the meltwater flowpaths that develop based on slope aspect and soil properties. The resulting flowpaths are shown to divert at least 4% of snowmelt laterally, accumulating along the length of the slope, to increase the snow water equivalent by as much as 170% at the base of a north facing hillslope. Results from this study show that snow acts as an extension of the vadose zone during spring snowmelt and future hydrologic investigations will benefit from studying the energy and soil together.
- 25 benefit from studying the snow and soil together.

1 Introduction

5

In many mountainous headwater catchments snow and soil moisture are key components of the hydrologic cycle, providing valuable information pertaining to the dynamic processes that occur during spring runoff. This has justified large data collection efforts to further understand the distribution of snow and soil moisture across landscapes during

- 30 the winter and spring seasons (Elder et al., 2009). During spring, much of snowmelt will infiltrate into the soil with a noticeable change in soil moisture prior to recharging groundwater storage, producing streamflow, or contributing to evapotranspiration (Bales et al., 2011; Kampf et al., 2015; Webb et al., 2015). The relative saturation in the vadose zone controls the stream connectivity and release of water and nutrients from subsurface storage into stream systems (McNamara et al., 2005; Williams et al., 2009b). Soil moisture during this time is driven by snowmelt that can impact
- the water availability for plant production (Molotch et al., 2009; Harpold et al., 2015) as well as the ionic signature of

soil moisture and stream flow (Harrington and Bales, 1998). For these reasons the connections between snowmelt and soil moisture are critical in understanding the hydrologic cycle in snow dominated headwater systems (Jencso et al., 2009), particularly in the face of a changing climate that will alter the snowmelt season and resulting hydrological dynamics (Adam et al., 2009; Clow, 2010; Clilverd et al., 2011; Harpold et al., 2012; Rasmussen et al., 2014; Fassnacht

5 et al., 2016).

Processes within headwater catchments such as snow accumulation and persistence are known to vary at multiple scales of interest. From a basin scale perspective, elevation has been shown to influence the depth and persistence of a snowpack (Richer et al., 2013; Molotch and Meromy, 2014; Sexstone and Fassnacht, 2014) while at finer resolutions the spatial variability of both accumulation and melt may be controlled by aspect (Williams et al., 2009a; López-

- 10 Moreno et al., 2013; Hinckley et al., 2014) and snow in forested areas are affected by interception during accumulation, shortwave radiation shading, and longwave radiation influences prior to and during melt (Storck et al., 2002; Musselman et al., 2008; Molotch et al., 2009; Adams et al., 2011; Webb, 2017). However, far less is known about the variability that snowmelt has on soil moisture and flowpaths during snowmelt at the hillslope scale, in large part due to the difficulty of observing soil moisture beneath a deep snowpack at high spatial resolution. Snowmelt is important
- 15 to soil moisture storage and resulting streamflow (McNamara et al., 2005; Williams et al., 2009a; Bales et al., 2011; Hunsaker et al., 2012; Kormos et al., 2014). Stream connectivity to the surrounding landscape follows seasonal trends with the highest connectivity during spring snowmelt based on factors such as topography (McNamara et al., 2005; Jencso et al., 2009; Jencso and McGlynn, 2011). The aspect of a hillslope will additionally increase soil water storage and retention on north aspect slopes (Geroy et al., 2011) that can alter runoff processes and result in spatially variable
- 20 soil moisture beneath a melting snowpack.

The ability to observe soil moisture throughout the water year has seen recent advancements for capturing high resolution data at both spatial and temporal scales (e.g. Bales et al., 2011). Similar advances have occurred for observing variables such as the liquid water content of a snowpack (Mitterer et al., 2011; Techel and Pielmeier, 2011; Koch et al., 2014; Heilig et al., 2015). This has allowed for further understanding of hydrological systems and dynamic

- 25 processes that are vulnerable to climate change (Bales et al., 2006). However, observations of the relative saturation of soil beneath a snowpack has been limited to an array of discrete points with sufficient instrumentation, and few studies have investigated spring snowmelt soil moisture at the similar scale as the snow above it has been measured. The few studies that have observed these process have shown microtopography to influence infiltration across the snow-soil-interface (SSI) (French and Binley, 2004) and that wetter areas tend to remain wetter with slope and aspect
- 30 being important factors at a low elevation site (Williams et al. 2009a). In high elevation alpine environments topography and wind shielding influences soil moisture distribution though there is less association to these parameters in low snow years (Litaor et al., 2008). These studies, limited to high alpine and low rain-snow transition zones, suggest that topographic influences on soil moisture are strong but more investigations during varying snow accumulation, melt dynamics, and environments are important to connect the distribution of soil moisture across a
- 35 <u>landscape to runoff processes</u>, particularly with variable regional and environmental snowpack responses to climate variability (Harpold et al., 2012), to connect the distribution of soil moisture across a landscape to runoff processes.

The relative saturation of the vadose zone determines runoff processes during spring snowmelt (McNamara et al., 2005). Runoff processes have been shown to change during spring snowmelt compared to summer rain events (Eiriksson et al., 2013; Williams et al., 2015). During snowmelt, soil moisture is influenced mostly in the top 10 cm of soil (Blankinship et al., 2014) with pulses of water that reach further depths varying widely at both the hillslope

- and catchment scale (Webb et al., 2015). At the catchment scale a south aspect hillslope may display matrix flow during snowmelt as the north aspect displays evidence of preferential flow through the soil (Hinckley et al., 2014). Preferential flowpaths have been shown to occur both in the soil beneath a snowpack (French and Binley, 2004) and above the ground surface within the snowpack (Marsh and Woo, 1985; Kattelmann and Dozier, 1999; Williams et al., 2000; Liu et al., 2004; Williams et al., 2010). Preferential flow within a snowpack can form as the result of ice lenses
- 10 (Colbeck, 1979) or differences in grain size and density (Avanzi et al., 2016; Webb et al., in review). Each of these can alter the flow of water through snow and resulting infiltration into the soil from the centimeter scale (Williams et al., 2010) up to tens of meters (Eiriksson et al., 2013; Webb et al., in review). Preferential flowpaths within a snowpack will create spatially variable snowmelt patterns across a landscape depending on the variable metamorphism that occurs within the snowpack (Yamaguchi et al., 2010; Adams et al., 2011; Domine et al., 2013; Katsushima et al.,
- 15 2013), which increases during melt (Marsh, 1987). These melt patterns have been shown to have correlation lengths of five to seven meters in relatively flat alpine terrain (Sommerfeld et al., 1994; Williams et al., 1999) and lesser correlation lengths of two to four meters in subalpine terrain (Webb, 2017). Preferential flowpaths within a snowpack will alter soil moisture and resulting runoff processes at the hillslope and catchment scales.
- To our knowledge there has not been a study investigating snow and soil moisture interactions specifically to 20 investigate hydrologic flowpath development in a sub-alpine environment beneath a deep (2 m) seasonally persistent snowpack. The goal of this study is to gain further understanding through observations of flowpath development in a snowmelt dominated subalpine headwater catchment. Observations of near surface soil volumetric water content (VWC) were compared to topographical parameters (e.g. slope, aspect, etc.) and hydrological variables (e.g. temperature, date of peak SWE, etc.). Statistical analysis of the topographical and hydrological controls on the spatio-
- 25 temporal variability of snow and soil moisture during snowmelt was undertaken at a subalpine forested setting with north, south, and flat aspects as a seasonally persistent snowpack melts through the following objectives: 1) investigate if evidence preferential flowpaths in snow can be observed and the effect on soil moisture through measurements of snow water equivalent (SWE) and near surface soil moisture, 2) observe how SWE and near surface soil moisture vary on hillslopes relative to the toes of hillslopes and flat areas, and 3) compare snowmelt infiltration beyond the
- 30 near surface soil between flat and sloping terrain during the entire snowmelt season.

2 Methods

To understand flowpath development during snowmelt and the resulting distribution of soil moisture, observations of SWE and near surface soil moisture were correlated to test the influence of topography and snow on soil moisture using Pearson's correlation coefficient, r, and a level of significance determined at p-values of 0.05 and 0.01. Near

measurement, near surface VWC on the first survey date, and topographic slope, elevation, and northness as calculated from a 10 m digital elevation model (DEM) (USGS, 2015). Northness is defined as the product of the cosine of aspect and the sine of slope (Molotch et al., 2005; Sexstone and Fassnacht, 2014).

2.1 Study Site

- 5 Data were collected over a 0.2 km² area near Dry Lake in Routt National Forest, approximately 6.5 km northeast of Steamboat Springs, Colorado (Fig. 1b). The elevation of measurement locations ranged from 2500 m to 2600 m with slope angles from 1° to 30° as determined from a 10 m DEM (USGS, 2015). The site has a mix of deciduous (aspen, populous tremuooides) and evergreen forest (subalpine fir, Abies lasiocarpa and engelman spruce, Picea engelmanii) with a majority of the vegetation growing near the small stream offering large areas of open canopy conditions (Fig.
- 10 1a) on each of the two predominant hillslopes (one south-southeast facing, and one north-northwest facing). The soils are primarily loams with very cobbly loam dominating the south aspect slope, cobbly sandy loam on the north aspect, and loam on the flatter aspects with observations of highly organic soils in the flat northeastern section of the area at the base of the north aspect hillslope (Table 1). Depth to bedrock was estimated using a one meter long hand auger at 16 locations within the study site along a transect from the top of the south aspect slope to the top of the
- 15 north aspect slope (Fig. 1b), resulting in soil depths ranging from 12 cm to greater than one meter at a single location. Soil depths tend to decrease with increasing elevation with a mean depth to bedrock of 40 cm and a median of 38 cm calculated from the 15 depths less than one meter (Fig. 1c). Sieve analyses were also conducted on six different volumetric samples of approximately 200 cm³ for near surface soil collected from four locations (two locations sampled twice) (Table 1).
- 20 For this study, regions were defined to compare observations on varying aspects and at the toes of hillslopes. Regions were defined as middle of the south aspect slope (SM), toe of the south aspect slope (ST), flat aspect (FA), toe of the north aspect slope (NT), low on the north aspect slope (NL), and high on the north aspect slope (NH) (Fig. 1c).

2.2 Spatial Surveys

Spatial surveys were conducted in 2013, 2014, and 2015. In 2013 two surveys were conducted four weeks apart while

- 25 in 2014 and 2015 four surveys were conducted at two week intervals. All survey periods began during the first week of April (April 6, 2013; April 4, 2014; April 3, 2015). Surveys consisted of a series of snow pits for collecting near surface soil moisture, snow depth, and bulk SWE data. At each pit location, the first measurements taken were near surface soil moisture using a handheld time domain reflectometer (TDR) (FieldScout TDR 100; Spectrum Technologies, Inc.) to measure the VWC using seven centimeter long prongs inserted vertically into the soil. A total
- 30 of five TDR measurements were averaged across the bottom of each snow pit (approximately one meter across, measurements ~20 cm apart). Volumetric soil samples (~40 cm³) were collected at three of the same point locations as TDR measurements in each snow pit for laboratory confirmation of VWC during surveys in 2013 and 2014. Bulk SWE measurements were collected using a plastic tube with an inner diameter of 68 mm and a length of 1.8 m. A core was collected for the full depth of the snowpack when possible, and in no more than two segments when the depth of
- 35 the snowpack was greater than the length of the tube. Snow cores were placed in a plastic bucket and mass measured

using a digital scale with 10 g precision. Two cores were averaged per snow pit with additional measurements if the first two showed greater than ten percent mass difference (a rare occurrence). When locations were returned to a new pit was dug within one to two meters with care to avoid previously disturbed snow. Additionally, snow density profile data were collected near a Snow Telemetry (SNOTEL) site on March 20, 2013; April 7, 2013; and February 20, 2015.

- 5 On April 6, 2013, 15 snow pits were measured and six were returned to and measured again on May 4, 2013 to capture the changes at the SM, ST, FA, NL, and NH regions (Webb and Fassnacht, 2016a). The 2014 and 2015 surveys collected data along approximate north-to-south transects perpendicular to topographic contours collecting multiple measurements in the six regions of interest. In 2014 a total of 25 snow pits were measured on April 4 and nine of these pits were returned to in two week intervals through May 17; eight of the nine pits were measured on April 19 (Webb
- 10 and Fassnacht, 2016b). The 2015 surveys made observations at 47 snow pits on April 3 and 23 of these pits were returned to on two week intervals through May 16 (Webb and Fassnacht, 2016c). Snow pit measurements were then averaged at each of the regions (SM, ST, FA, NL, and NH) for each day of observations.

2.3 Time Series Data

- At the study site, there are two stations that measure meteorological variables including air temperature, relative humidity, precipitation, wind speed and direction, and solar radiation. The Dry Lake Remote Automated Weather Station (RAWS station coCDRY and National Weather Service ID 050207, <raws.dri.edu>) is along an exposed ridge at the top of the south aspect slope at approximately 2540 m elevation and has been operated by the United States Forest Service since 1985 (Fig. 1a and 1b). Additionally, hourly dewpoint and wet bulb temperature, snow depth, and SWE are measured at the Dry Lake SNOTEL (station 457 <wcc.nrcs.usda.gov>) station located approximately 120
- 20 m to the south-southwest of the RAWS at a lower elevation of 2510 m with light canopy shading (Fig. 1a) and has been operated by the Natural Resources Conservation Service since 1980 measuring SWE and precipitation. Since 2003, this SNOTEL station has additionally measured soil moisture and temperature at three depths (5 cm, 20 cm, and 50 cm). The RAWS and SNOTEL data provide meteorological data at two elevations and different canopy conditions within the relatively small area of interest of this study.
- 25 Snowmelt infiltration observed by the SNOTEL station is for a relatively flat location, and thus was compared to additional soil moisture and temperature instruments that were installed on the north aspect slope on December 27, 2013 at depths of 5 cm, 12.5 cm, and 20 cm. The top and bottom depths match two of the SNOTEL soil moisture depths; the 12.5 cm depth sensor was added at mid-depth between the other sensors. Instruments installed were Decagon Devices, Inc. 5TM temperature and moisture sensors connected to a Decagon Em50 data logger. Installation
- 30 in December 2013 required disturbing the snowpack and soil, thus the snowpack and soil moisture were allowed to return to near undisturbed conditions after installation and data prior to March 15, 2014 was not included in analysis. The soil moisture sensors and data logger were calibrated prior to installation using approximately 1500 cm³ of soil collected from the study site and tamped around a sensor to a density of 1.0 g cm⁻³, similar to measured conditions in the field. The calibration occurred at a constant temperature of 0.5°C and additions of seven to ten percent VWC every
- 35 four days. The container mass was recorded to confirm mass of soil, sensor, and water as well as the sensor reading

of temperature and VWC prior to the addition of water each time. All mass recordings were at a precision of 1.0 g (volumetric water precision of 0.06%) and VWC sensor recordings to 0.1%.

3 Results

3.1 Time Series Snow and Meteorological Data

- 5 The three spring snowmelt seasons studied represent varying melt conditions. Average peak SWE occurs at the Dry Lake SNOTEL station on April 5 with a 35 year median peak of 570 mm and a mean of 590 mm (Fig. 2a). Peak SWE values recorded at the SNOTEL station were 495 mm, 715 mm, and 415 mm for 2013, 2014, and 2015, respectively, representing 87%, 125%, and 73% of the station long term median. Peak SWE timing ranged from the earliest on March 9 in 2015, preceding first survey by nearly one month, to the latest on April 25 in 2013, 19 days after the first
- 10 survey (Fig. 2a). The number of days from peak SWE to no snow recorded at the SNOTEL station ranged from the fewest in 2013 of 22 days in 2013 to the most in 2015 ofto 52 days days in 2015, with each year having incremental snowfall during the melt period (Fig. 2b). Precipitation at the SNOTEL station during the survey periods was 130 mm for 2013, 100 mm for 2014, and 2015 accumulated 115 mm from the date of the first survey to the last survey (Fig. 2b). The precipitation that fell during the melt period in 2015 likely included a number of rain-on-snow events due to
- 15 the regular warmer than freezing temperatures in late April and May (Fig. 2d), though snow can fall at several degrees warmer than zero (Fassnacht et al., 2013). On March 1st, the snow accumulation was the same in 2013 and 2015, with approximately 40% more in 2014; the subsequent spring snowpack variability between years was a result of varying meteorological forcing conditions during March, April, and May (Fig. 2). The SNOTEL station data show air temperature during these months warmer than freezing 62%, 64%, and 77% of the time and cumulative solar radiation
- 20 totaled 355 kW, 380 kW, and 400 kW in 2013, 2014, and 2015, respectively (Fig. 2c). Wind directions remained consistent each year during the spring months, generally from the southwest and northeast alternating diurnally between directions (Fig. 2e). The RAWS site showed slightly larger diurnal temperature fluctuations, greater cumulative solar radiation, and less precipitation during the spring snowmelt seasons relative to the SNOTEL station, though generally similar conditions were observed when comparing the two stations (Fig. 2).

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These conditions resulted in snow density profiles that display<u>ed indicators ofthin</u> melt-freeze crusts and ice lense formation (Fig. 3). It should be noted that the location of these snow pits near the SNOTEL station contains a lot of buried vegetation and large rocks causing difficulties in obtaining density measurements near the ground surface. The 2013 melt season observed the development of a higher density layer near 70 cm above ground that deteriorated in the time between observations, though a higher density layer formed at ~80 cm above ground, likely as the result of melt-freeze cycles. The February, 2015 density profile observed a similar high density layer near 70 cm above ground, though additional higher density snow is observed closer to the ground (Fig. 3). These density profiles provide observations of density profiles near peak SWE for 2013 and 2015 with average densities between 350 and 370 kg m⁻

³ during the varying meteorological conditions each year, respectively.

3.2 Spatial Surveys

The variable meteorological influences on the snowpack and soil moisture was observed through the spatial surveys. Surveys conducted in 2013 and 2014 occurred while a measureable snowpack was still observed at the SNOTEL station for all survey dates whereas in 2015 the SNOTEL station measured zero snow for the final two of the four

- 5 surveys resulting in variable conditions for SWE and VWC measurements each year. In 2013 all north aspect locations increased in SWE between surveys with the largest increase occurring at the toe of the north aspect slope (NT, 160 mm) and the smallest increase high on the slope (NH, 20 mm) (Fig. 4bi). SWE also increased at the toe of the south aspect slope (ST, 90 mm) and decreased in the middle of the south facing slope (SM) (Fig. 4bi). In 2014 a similar pattern was observed of increases in SWE at the toes of each slope (ST and NT) and lesser increases on the north
- 10 facing hillslope (Fig. 4biii), though low on the slope one pit location decreased in SWE and another remained the same (Fig. 4aiii). Increases in SWE occurred early in the melt period for 2013 and 2014 whereas the early melt period was not observed in 2015 due to the early peak accumulation. After the initial increase in SWE for some locations during the first melt period observed (MP-1), all locations decreased in SWE for the two following melt periods (Fig. 4b). In 2015, SWE did not change during MP-1 at NT and ST regions, while it decreased at the four other locations
- 15 (Fig. 4bv). This is less of a decline in regions that increased for 2013 and 2014. At the toes of each slope in 2014, the increase in SWE during the first melt period was larger than the decrease in the following two melt periods combined (Fig. 4). In 2015, only two measurement locations had snow during the final survey (May 16) and precipitation influenced observations (discussed later).
- In 2013 and 2014 were-evidence of lateral flow in the form of frozen ice "veins" immediately above the snow-soil interface (SSI) were observed <u>during the early meltseason surveys</u> (Fig. 5). These were observed on the north aspect (NL and NH) and at the toe of the north aspect slope (NT) only and appeared to be continuous, though continuity was only confirmed for three to four meters based on excavation. The occurrence of this phenomenon was in the direction of the hillslope fall line and on ground that was not super-saturated. These ice "veins" were not observed in 2015 though they may have occurred prior to our observations since the early meltseason was not observed that year. Also
- 25 qualitatively observed was the relative density of snow in each pit in 2014. Observed i<u>I</u>ce lenses were observed in the snow stratigraphy were only observed on the north hill slope and in only about one-third of the observed locations on the hillslope. <u>Also qualitatively observed was the relative density of snow in each pit in 2014.</u> <u>Additionally oO</u>n the north aspect slope, snow density tended to decrease with height above the SSI, with heavy wetter snow remaining in the bottom of the snowpack in the form of saturated snow at the bottom of each pit. These saturated snow layers
- 30 increased in depth downslope and were only observed at the bottom of the snowpack directly above the SSI. The near surface soil VWC during all surveys varied from mean values of 15% to 85% (Fig. 4). The maximum soil moisture consistently occurred at the toe of the north aspect hillslope (NT) in the highly organic soil. The soil at this location was also observed to be super-saturated during a single survey on April 19, 2014 (resulting in the 85% VWC and surface ponding, Fig. 4bii). The near surface soil VWC showed variable observations of increasing and decreasing
- 35 soil moisture beneath a melting snowpack with relatively larger decreases immediately following snow disappearance (Fig. 4a).

The 2015 surveys resulted in the largest variability of measurements each survey for both SWE and near surface VWC (Fig. 4c). The early peak accumulation resulted in only two measurement locations with snow for all four survey dates. However, as with previous years, near surface VWC decreased noticeably after the disappearance of snow for all locations with some increases due to rain events (Fig. 4eii4b).

5 **3.3 Spatial Correlation**

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The topographic parameters of elevation, slope, and northness showed mostly low correlations to near surface VWC during observations and little significance at the 0.05 level (Table 2). The only topographic parameter that resulted in a Pearson's r value of magnitude larger than 0.5 was slope, occurring later in the 2014 observation period. The only topographic parameter that showed any significance was northness on May 16, 2015, when soil had been exposed to the atmosphere from loss of snow for 93% of measurement locations.

- Measurement locations were also tested for correlation of hydrologic variables to near surface VWC that included SWE, Δ SWE, first measured SWE, and first measured VWC. These variables showed higher correlations and more occurrences of significance at the 0.05 and 0.01 level relative to topographic parameters (Table 2). The highest Pearson's r values of all variables to near surface VWC was the first measured near surface VWC that are positive
- 15 and all but one correlation being significant at the 0.01 level. Pearson's r values tend to decrease in magnitude for this variable as time from the first survey increases (Table 2).

The correlation of SWE variables to near surface VWC were inconsistent in strength, direction, and significance with a lot of variability each survey. The mostly negative correlations for near surface VWC to Δ SWE indicate that in 2013 and 2014 locations with lesser changes in SWE had higher near surface VWC, though this was significant at the 0.05

20 level on April 19, 2014 only (Table 2). The similar negative correlation and magnitudes of near surface VWC to first measured SWE show that in 2013 and 2014 areas that had less SWE during the first survey tended to have higher measured VWC<u>at later dates</u>, significant at the 0.05 level on April 19, 2014, and at the 0.01 level on May 3, 2014 (Table 2).

3.4 VWC Time Series Data

- 25 Soil moisture and temperature sensors clearly show the diurnal fluctuation of VWC from snowmelt infiltration across the SSI and the fluctuation in soil temperature as snow disappears (Fig. 6). Soil temperatures at 5 cm depth remain between 0°C and 1°C through winter and temperatures begin to fluctuate in the soil at approximately the same time of snow disappearance (Fig. 6). This temporal pattern occurs at both the SNOTEL station and on the north aspect slope. These locations also show the relatively quick drying after snow disappearance in 2014 and slower drying as a
- 30 result of rain in 2015. However, there is more drying between rain events on the flat aspect Fig. 6 compared to the north aspect slope (Fig. 6b). At the flat aspect SNOTEL station the VWC sensors at 5 cm and 20 cm depths follow a similar temporal pattern remaining within 5% of each other the entire winter season indicating snowmelt infiltrating and wetting the soil at 20 cm depths and a higher relative saturation in entire vadose zone (Fig. 6bi). Beneath the snowpack and during melt, the north aspect hillslope VWC sensors show a difference of approximately 15-20% with
- 35 more similar VWC observed during summer and fall rain events (Fig. 6bii). This is more pronounced in 2015 where

the 2014 season may have been impacted by the mid-winter installation of the sensors. The 12.5 cm deep sensors on the north aspect slope also displays a more similar VWC value to the 20 cm sensor with values drier than the 5 cm sensor indicating less snowmelt infiltrating and wetting the soil at 12.5 cm and 20 cm depths, The lower VWC values at 20 cm depth shows and a lesser relative saturation in the vadose zone on the north facing slope (Fig. 6bii) compared

5 to flat terrain (Fig. 6bi).

> Rain events that occurred prior to soil moisture drying in May, 2015 resulted in infiltration excess overland flow due to high intensity precipitation. These events occurred prior to new vegetation becoming established on the hillslope. Evidence of overland flow was observed during the May 16, 2015 survey when most of the snow had disappeared on all hill slopes and the dead grasses from the previous summer were lying flat on the ground and vegetation litter piled

10 up in the downslope direction; this was not the observed state of the dead grasses and litter in snow free areas during the previous survey on May 2. During the overland flow event(s), differences in VWC measurements at 5 cm, 12.5 cm, and 20 cm deep sensors on the north aspect slope are similar to what is observed during the snowmelt season and not what is observed during rain events during the summer and fall (Fig. 6bii). However, the flat aspect VWC sensors displayed similar patterns during nearly all rainfall or snowmelt events (Fig. 6bi). These observations indicate that 15 less snowmelt infiltrates to the 20 cm depth on the north facing slope relative to the flat aspect (Fig. 6b) and that

snowmelt water is flowing downslope near the SSI (Fig. 5).

4 Discussion

The multiple years of observation at a subalpine location with a deep seasonally persistent snowpack offers analysis of SWE and near surface VWC patterns that have previously been limited to lower elevations near the rain-snow 20 transition zone (Williams et al., 2009a) and higher elevations in an alpine environment (Litaor et al., 2008). In this study, the only topographic parameter that displayed any significance on the near surface soil moisture at the 0.05 level was northness and this appeared to increase in significance and strength with time indicating that it is likely more related to the presence or absence of snow and influences from rain (Table 2). However, infiltration of snowmelt beneath the near surface to 12.5 cm or 20 cm depth was influenced by slope with more infiltration wetting the soils at 25 20 cm depth on the flat aspect and lesser wetting at this depth on the north aspect in the early meltseason (Fig. 6b) where observations of ice "veins" and saturated layers of snow were made at the SSI (Fig. 5). The soils on the south aspect slope are generally coarser than the north or flat aspects (Table 1), suggesting that soil water retention is higher on north aspects (Geroy et al., 2011). This was reflected with the north aspect soils often having similar and/or higher water contents than south aspect soils, both with and without the presence of a snowpack (Fig. 4, SM vs. NL and NH). 30 Near surface soil moisture approached relative equilibrium with a persistent snowpack rather than varying through time (Fig. 4, Fig. 6b). As the snowpack melts the shallow subsurface VWC displays clear diurnal fluctuations (Fig. 6b). The locations that were wet relative to the other locations during the first survey remained as such for all following surveys when snow persistently covered the study area comparing well to the study by Williams et al. (2009a) at a smaller scale and beneath a shallow snowpack near the rain-snow transition zone at a lower elevation. However, in contrast to Williams et al. (2009a), near surface VWC showed a negative correlation to the first measured SWE (representative of peak) in 2013 and 2014. This negative correlation indicates that locations with lower peak SWE

(During the first survey of the season) tend to have greater VWC at the later surveys. resulting from locations with deeper snowpacks having lesser near surface VWC and shallower snowpacks having greater near surface VWC. This is the result of the shallower snowpacks during the first survey being near the bottom of the slopes and in the flat terrain influenced by canopy interception (Fig. 1a) that yields a lower peak SWE and the following followed by melt

- 5 flowing flows downslope at the SSI towards these locations and increasing both SWE and near surface VWC during the following surveys (Fig. 4). Though in 2015, a relatively low snow year, results agreed with Williams et al. (2009a) of higher near surface VWC at locations that accumulated more snow indicating the amount of snowfall is also important to these processes. During low snow years, areas where snow persists longer will result in a longer influence on near surface soil moisture. Near surface VWC will additionally depend on variability in soil parameters such as
- 10

affect the infiltration or lateral flow of meltwater at the SSI when on a slope. Meltwater flowing downslope near the SSI on the north aspect hillslope is shown by the increases in SWE at locations on and at the toe of the hillslope (Fig. 4), the frozen "ice veins" observed <u>in 2013 and 2014 early meltseasons</u> (Fig. 5), less infiltration to <u>12.5 cm and</u> 20 cm depth on the slope (Fig. 6), similarities in soil moisture between snowmelt and

soil water retention, with higher moisture retention from finer soil particles, similar to the north aspect slope, will

- 15 overland flow rain events, and the observations of snow density and wetness increasing with depth downslope in each north aspect snow pit. For the south aspect slope, the increases in SWE at the ST locations were similar to observed precipitation in 2013 and an increase in snow depth for 2014. The south aspect slope may have meltwater flowing downslope near the SSI, though to a lesser extent than the north facing slope and less apparent. The movement of water across layer interfaces has been shown within a snowpack (Williams et al., 2000; Liu et al., 2004; Williams et al., 2004; Willi
- 20 al., 2010) and at the SSI (Eiriksson et al., 2013), with evidence of the latter being observed in this study (Fig. 5). This phenomenon will depend on soil parameters, snowpack layer characteristics, slope angle, and the rate that meltwater is percolating through the snowpack. These factors will determine if an interface acts as a permeability barrier, similar to a soil drain, or a capillary barrier (Avanzi et al., 2016; Webb, 1997; Webb et al., in review). Evidence of flow at the SSI was not observed on the south facing slope (Fig. 4). This hillslope has coarser soil and different meteorological
- 25 forcing on snowmelt that increases the rate of water percolation due to higher solar radiation loading (Fig. 2c). This increased radiation loading will also increase the rate of equilibrium snowpack metamorphism (to rounded grains) causing the snowpack to be less stratified relative to the flat or north aspect snowpacks. Results of this study suggest that meltwater is flowing at the SSI and downslope through the snowpack on the north aspect hillslope but not on the south aspect hillslope. The primary reasons for lateral flow through the snowpack at this location on the north facing
- 30 slope is a result of the slower melt rates on the north aspect slope and smaller hydraulic conductivity of the soil. When capillary barriers occur, the diversion length will be controlled by the hydraulic properties of the media, slope of the interface (steeper slope increases diversion length), and infiltration rate (slower infiltration rate increases diversion length) (Webb, 1997; Webb et al., in review). It is also possible for lateral flow to be caused by barriers within a layered snowpack well above the SSI, though the large saturated layer of snow was observed only at the SSI in all
- 35 north aspect snow pits shows showing that this is where the bulk of the lateral flow occurs. Further testing and field experiments are necessary to quantify the influence of varying slope and soil parameters on these processes in and below a snowpack. Our study shows preferential flowpaths during snowmelt on the north facing slope that are similar

to an alpine catchment with water flowing through the snowpack downslope (Liu et al., 2004, Williams et al., 2000), during rain on snow events at lower elevation sites (Eiriksson et al., 2013), and observations in a coastal climate (Kattelmann and Dozier, 1999).. These processes can be combined into a conceptualization of the northern aspect slope having meltwater flowpaths near the SSI downslope and the southern aspect slope having more infiltration into

- 5 the soil (Fig. 7). Coarse soil can also divert water in the form of a capillary barrier as observed by Eirikkson et al. (2015) at the rain snow transition zone, though this was not observed in our study. The north aspect slope has preferential flowpaths during snowmelt that are similar to an alpine catchment with water flowing through the snowpack downslope (Liu et al., 2004, Williams et al., 2000), during rain on snow events at lower elevation sites (Eiriksson et al., 2013), and observations in a coastal climate (Kattelmann and Dozier, 1999). The soil,
- 10 snow, topographic characteristics, and rate of snowmelt create an environment on the north aspect slope that separates vertically percolating meltwater into flowpaths that travel across the SSI and downslope (Fig. 5) increasing SWE at downslope (Fig. 4) and allowing some water to infiltrate across the SSI similar to a permeability barrier (Fig. 6bii) (Webb et al., in review). The south aspect slope coarser soil, less stratified snow, and higher rates of snowmelt due to increased solar radiation that produce less observed flow laterally at the SSI, and more infiltration into the soil. These
- 15 processes can be combined into a conceptualization of the northern aspect slope having meltwater flowpaths near the SSI downslope and the southern aspect slope having more infiltration into the soil (Fig. 7). Coarse soil can also divert water in the form of a capillary barrier as observed by Eirikkson et al. (2015) at the rain snow transition zone, though this was not observed in our study. The slope of the hill will also affect this phenomena (Webb, 1997; Webb et al., in review) and in this study the north aspect slope is steeper than the south aspect (Fig. 1) though further testing is
- 20 necessary at multiple slope angles to investigate how slope controls this process, since both north and south slopes are steep enough to produce hydraulic barriers (Webb, 1997; Webb et al., in review).

As hydraulic barriers form and promote flowpaths to develop within the snowpack such as on the north aspect slope, the timing of runoff at the hillslope scale can change dramatically. Snow has been shown to have a hydraulic conductivity orders of magnitude greater than common soils (Yamaguchi et al., 2010; Domine et al., 2013) and will

- 25 thus be important for hydrologic modeling and flood prediction from snowmelt runoff. From a groundwater recharge perspective, much of the hydraulic gradients driving subsurface flow will be occurring at the base of the north aspect hillslope in this study area due to the lateral flow of water through the snowpack and soil moisture sensors on the slope will only account for a fraction of the total meltwater as flowpaths bypass sensor profiles. Also, at the base of the hillslope (NT) the snowpack can increase in bulk SWE by up to 250 mm (from 146 mm to 396 mm, Fig. 4e4aiii)
- 30 displaying the increased-the storage capacity of a location by the <u>porosity of the snow</u>. and <u>This will</u> resulting in areas of focused recharge and variable infiltration in the subsurface as observed in other subalpine regions (Webb et al., 2015). However, hillslopes can still display a more classical conceptualization of snowmelt infiltration uniformly and travelling across the soil-bedrock interface to recharge groundwater resources and generate streamflow as on the south aspect slope (Fig. 7) and later in the summer on the north aspect slope (Fig. 6bii).
- 35 In order to estimate the ratio of lateral flow vs. infiltration on the north aspect slope an energy budget calculation was conducted. The energy budget was calculated assuming an isothermal snowpack on the date of peak SWE observed at the SNOTEL station and utilizing the SNOTEL measured air temperature, relative humidity, wind speed,

precipitation, and short wave radiation. Fraction of cloud cover was estimated from comparing clear sky expected shortwave radiation based on latitude and time of year to observed solar radiation at the RAWS location based on Fassnacht et al. (2001). This estimated energy budget was calibrated through adjustments to the longwave radiation component to match average SWE losses at the SNOTEL station. The north aspect energy budget was then estimated

- 5 through altering the shortwave radiation component only by a factor of 0.7 based on average slope and aspect for the month of April. This resulted in an approximated average melt rate on the north facing hillslope of 0.6 that of the SNOTEL station. Using the 10 m DEM we estimated average contributing areas for the snow pit locations on the north facing slope. We then used the changes in SWE and observed precipitation to estimate the contribution of lateral flow for the two week periods between observations. Given the observed increases in SWE along theon the -250 m
- 10 long-north facing hillslope this results in a minimum of 4% of melt traveling laterally above the SSI to produce the observed increases in SWE. The 4% is water that flows downslope above the SSI and remains in the snowpack. Therefore, the percentage may be larger when considering drainage from the snowpack after flowing laterally. Though 4% of melt flowing downslope within a snowpack is a low number it accumulates along athe 250 m -250 m hillslope to increase the SWE at the toe of the slope the most. byThe 170% increase in SWE at NT as observed in 2014 (Fig.
- 15 4) is likely a result of both water flowing above the SSI and below it causing the water table to rise, though the increases in SWE at NL can be attributed to flow above the SSI. Estimating SWE from depth measurements alone in this location-area will be inaccurate when not considering the effect of preferential flowpaths within the snowpack and the resulting effects on snow density.

Preferential flowpaths and aspect controls during snowmelt have been observed at lower elevations. At a different site

- 20 in Colorado, near the rain-snow transition zone, the intermittent snowpack on south aspects displayed matrix flow whereas north aspects displayed preferential flowpaths through the soil (Hinckley et al., 2014). These results are similar to those observed in the present study during the 2015 snowmelt while the 2013 and 2014 seasons displayed what can be interpreted as lesser melt rates on the north versus south slopes due to temperature and radiation differences (Fig 2c and d) that result in the preferential flowpaths near the SSI. In this study, the north aspect slope
- 25 displays preferential flowpaths early in the snowmelt season similar to alpine regions (Liu et al., 2004; Williams et al., 2015) that can transport a large amount of water relative to the following melt periods (Fig. 4ai and bi). Flowpaths then transition to more uniform melting and less preferential flow as the melt season progresses. In 2015, this may have also occurred prior to our observation period, though this is uncertain. The south aspect slope is similar to slopes at lower elevations near the rain-snow transition zone (Eiriksson et al., 2013; Hinckley et al., 2014) that display
- 30 uniform melt and matrix type of flow with small amounts of water diversion at the SSI. In 2013 the increase in SWE at the toe of the north facing slope was 30 mm greater than the amount of precipitation that was recorded (Fig. 4a). The increase in SWE downslope is occurring from the accumulation of meltwater flowing across the SSI (Fig. 7). Wind is not likely causing increased deposition on any particular part of a hillslope since winds run perpendicular to slopes (Fig. 2) and depth decreased (Fig. 4). Though snow drifts may still occur, care was taken
- 35 during measurements to avoid areas with noticeable wind drifts, or where drifts would likely occur due to the predominant wind directions. In 2014, the large increase in SWE at the toe of the north aspect slope (NT) is from the lateral flow of water in snow and the rising of the water table above the soil surface (Fig. 4bi) as evidenced through

observations of a deep saturated layer at the bottom of the snowpack and saturated soils. This is a result of snowmelt primarily influencing the top 10 cm of soil on the slope (Blankinship et al., 2014) and water flowing downslope near the SSI decreasing the travel time of water on the hillslope and increasing connectivity at the toe of the hillslope and water table similar to observations in the northern Rocky Mountains (Jencso et el., 2009). Some locations on the north

- 5 aspect slope in 2014 remained consistent in the amount of bulk SWE as other locations on the hillslope decreased in SWE due to preferential flowpaths causing non-uniform flow across the hillslope (Fig. 53). The final-2015 surveyobservations shows similar increases in SWE between surveys that are show the result of rain-on-snow events occurring that are known to produce lateral flow within snowpacks (Eiriksson et al., 2013). The major difference of 2015 is earlier peak SWE and melt season along with increased solar radiation and warmer temperatures (Fig. 2). It is
- 10 also difficult to determine if this would be isolated to the north aspect hillslope in 2015 since there is a lack of snow on the south facing slope during the rain on snow events. It is possible that preferential flowpaths caused more lateral diversions earlier in the season, however no evidence of this was observed in our study. Future hillslope scale investigations of these phenomena may benefit from larger scale runoff lysimeter studies similar to Eiriksson et al. (2013) and observing the entire melt season to capture peak SWE processes in low years.
- 15 In flat terrain, snowmelt patterns are known to have correlation lengths of five to seven meters in alpine environments (Sommerfeld et al., 1994; Williams et al., 1999) and two to four meters in a subalpine environment (Webb, 2017). These correlation lengths are less than the distances between measurement locations in this study. However, these correlation lengths are explained by flow across snow layer interfaces and snow topography in flat terrain (Sommerfeld et al., 1994; Williams et al., 1999; Williams et al., 2010). Increasing the topographic slope will thus increase the
- 20 correlation lengths as the snow layer interfaces tilt with the slope of the ground (Webb, 1997; Webb et al., in review). This study shows that the resulting correlation lengths in complex terrain with steep slopes can increase towards the scale of the terrain variability and result in increases in SWE at the toes of hillslopes. Further investigations are necessary to determine the scale that water may flow through snow or at the SSI on steep slopes. Future studies will benefit from the use of numerous soil moisture sensors to obtain time-series data of soil VWC at multiple locations
- 25 within a watershed to observe the variable infiltration characteristics during snowmelt that is difficult to detect from the near surface soil moisture alone.

When considering dynamic hydrologic processes that occur during spring snowmelt in subalpine headwater catchments, it is important to consider the variable flowpaths that develop based on factors such as slope, aspect, soil parameters, and snowpack characteristics to move beyond single point measurements and one-dimensional

30 assumptions. The toe of a hillslope is an important location to observe and estimate the amount of hillslope runoff occurring near or above the SSI relative to flow through the soil in future investigations. Future studies will benefit from considering the snowpack as an extension of the vadose zone during spring snowmelt due to the variable saturated flow that occurs.

5 Conclusions

35 The observations of this study occurred during above normal, relatively normal, and below normal snow seasons capturing bulk SWE and soil VWC variability in space and time during spring snowmelt with varying meteorological

forcing conditions, including rain-on-snow events in 2015. Evidence was presented of preferential meltwater flowpaths at the snow-soil interface on the north aspect hillslope during early snowmelt. The effect of these preferential flowpaths were observed in changes in SWE and infiltration in the shallow subsurface at 20 cm depth, but not observed in the near surface soil moisture. Near surface soil moisture is correlated the strongest to soil moisture

5 measured during the first survey than to other topographic parameters or hydrologic variables. Infiltration beyond the near surface occurred more on flat terrain when compared to sloped conditions during the entire snowmelt season, resulting in greater relative saturation in the shallow subsurface in the flat area. The snowpack is a porous medium that is an extension of the vadose zone and increases the water storage capacity of

a region within a watershed. Water flowing downslope near the snow-soil-interface increased SWE at the toe of the

- 10 north aspect hillslope by as much as 250 mm (170 %) that additionally effects the soil moisture at the toe of the slope. This is a result of a minimum of 4% meltwater being directed downslope through the snowpack rather than infiltrating. The south aspect hillslope did not display evidence of this phenomenon. The differences in flowpath development on the two opposite facing hillslopes is due to differences in soil, snowpack characteristics, slope and aspect, and snowmelt rates as a result of meteorological forcing variability. The formation of hydraulic barriers at the snow-soil
- 15 interface will be dependent upon the snow characteristics, soil parameters, and meteorological conditions during melt. During 2015 when a relatively low peak SWE occurred early and rain-on-snow events were observed, the variability of snow and soil moisture increased displaying the connection and interactions between snow and soil moisture. Results from this study show that the snow acts as an extension of the vadose zone during spring snowmelt and future investigations will benefit from studying both the snow and soil together.

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Figure 1: a) Panoramic picture of the study area facing east to southeast. Location of photo taken to the west of RAWS location in map
 (b). Locations of the Remote Automated Weather Station (RAWS), SNOTEL station, and installed soil moisture sensors are circled and labeled. b) Map of the study site and area of interest in this investigation. 10 m contours are shown. c) Cross section A-A from panel (b) showing the elevation of the ground surface and depth to bedrock using a 100 cm long hand auger. Regions of interest are identified as middle of the south aspect hillslope (SM), toe of the south aspect slope (ST), flat aspect (FA), toe of the north aspect slope (NT), low on the north aspect slope (NL), and high on the north aspect slope (NH). All ground surface data are 10 m resolution digital elevation model (USGS, 2015).



Figure 2: a) Daily Snow Water Equivalent (SWE) measured at the SNOTEL station each spring of the study period and the 35 year median of the station measurements, b) cumulative precipitation occurring during the spring survey study periods of April and May as measured at the SNOTEL and RAWS site, c) cumulative solar radiation at the SNOTEL and RAWS sites during spring, d) mean daily temperature at the SNOTEL and RAWS sites during spring, and e) wind rose of spring data for the three years studied at the SNOTEL site.



Figure 3: Observations snow density profiles on March 20, 2013; April 7, 2013; and February 20, 2015.



Figure 4: Observations of a) measured values for snow water equivalent (SWE) and near surface soil volumetric water content (VWC) and b) changes in measured values between survey dates for regions of interest: middle of the south aspect hillslope (SM), toe of the south aspect slope (ST), flat aspect (FA), toe of the north aspect slope (NT), low on the north aspect slope (NL), and high on the north aspect slope (NH). Also included are observed values at the SNOTEL site (SNO) that include SWE and precipitation (Precip.) with precipitation that fell when air temperature (Tair) was greater than 1°C shown in red. Figure panels display i) 2013 SWE, ii) 2013 VWC, iii) 2014 SWE, iv) 2014 VWC, v) 2015 SWE, and vi) 2015 VWC. Changes are shown for melt period 1 (MP-1) between the first two surveys, melt period 2 (MP-2) between the second and third surveys, and melt period 3 (MP-3) between the third and fourth surveys. Each melt period is 14-15 days with the exception of 2013 that was 28 days. Error bars indicate total range of measurements at locations.



Figure 5: Picture of frozen ice "vein" observed at the snow-soil-interface (SSI) providing evidence of lateral flow of meltwater occurring within the snowpack. Foot shown for scale.



Figure 6: a) Daily snow water equivalent (SWE) and precipitation recorded at the Dry Lake SNOTEL station and b) the hourly soil volumetric water content (VWC) and 5 cm deep temperature at bi) the flat SNOTEL site and bii) the installed sensors on the north aspect slope.



Figure 7: Conceptual model of flowpaths that develop during early spring snowmelt at the south aspect hillslope (SM), toe of south aspect slope (ST), flat aspect (FA), toe of north aspect slope (NT), low on the north aspect hillslope (NL), and high on the north aspect hillslope (NH).

10 Table 1: Percent of grain sizes by mass determined from sieve analysis of samples collected using a ~200 cm³ sample at locations in the middle of the south aspect slope (SM), the toe of the south aspect slope (ST), flat aspect (FA), and low on the north aspect slope (NL). Fines are considered less than 0.074 mm, sand is larger than fines and less than 4.75 mm.

	SM	ST	FA	NL
Percent Fines	21	25	29	29
Percent Sand	46	61	64	58
Percent Larger	33	14	7	13

Table 2: Results of pattern analysis of near surface soil moisture measurements based on slope angle, northness (north.), elevation (elev.), Snow Water Equivalent (SWE), change in SWE (Δ SWE), SWE on first survey of the year, and near surface soil moisture (VWC) on first survey of the year. Significance is shown with table cell shading and bold text representing a p-value less than 0.05 and <u>underlined text</u> a p-value less than 0.01.

		slope	north.	elev.	SWE	ΔSWE	1 st SWE	1 st VWC
2013	6-Apr	0.19	0.327	0.02	0.52			
	4-May	0.12	0.090	0.12	-0.25	-0.68	-0.57	<u>0.92</u>
2014	4-Apr	-0.21	0.006	-0.12	-0.36			
	19-Apr	-0.40	0.070	0.03	-0.08	-0.82	-0.83	<u>0.99</u>
	3-May	-0.63	0.410	-0.02	0.30	-0.38	<u>-0.89</u>	<u>0.95</u>
	17-May	0.57	0.494	-0.40	0.62	-0.48	-0.39	<u>0.82</u>
2015	3-Apr	-0.18	0.181	-0.22	0.12			
	17-Apr	-0.08	0.262	-0.01	<u>0.56</u>	-0.09	0.47	<u>0.95</u>
	2-May	0.11	0.015	0.26	<u>0.87</u>	0.36	<u>0.56</u>	<u>0.80</u>
	16-May	0.06	<u>0.417</u>	0.26	0.46	0.50	0.15	0.48