

Response to reviewer comments on HESS-2019-214: “Are the effects of vegetation and soil changes as important as climate change impacts on hydrological processes?” by Rasouli, Pomeroy and Whitfield

**Editor’s Comment:**

Thank you for your detailed comments addressing the reviewers concerns. At this time, I would ask you to submit a revised manuscript that has addressed the substantive issues for consideration.

**Response:**

Thank you very much for reviewing the response to the reviewers’ comments. As requested, we uploaded the revised manuscript with almost 80% rewriting the text of the manuscript and revising most of the results and figures.

**Referee #1:** HESS-2019-214-RC1

This paper presents a study of changes to hydrological processes under shifting climate, soils and vegetation. The paper is very interesting and the manuscript presents a novel, challenging and important study. However, the current presentation of the work makes it very difficult to really understand what is being said and follow the (complex) findings of the work. I have made some suggestions for the authors to consider on how to organize the presentation that may assist the reader to better follow, understand, and derive a meaningful message from this work.

\*\*\*\*\*AC: The comments and suggestions of Reviewer #1 were very helpful in improving this manuscript. We have rewritten the manuscript to make the presentation of a complex study easier to follow. We have reduced the number of acronyms, using the basin names instead of letter codes and use a consistent letter code to refer to the eight cases that cover the present and future climates, vegetation, and soils.

-The Introduction is not well organized and I suggest rewriting and reorganizing it to develop the argument on why this study is necessary, and why it is important. For example, the very first line of the Introduction discusses the French Alps. Is the paper about the Alps? I don’t think it is. The rest of this paragraph is devoted to a somewhat rambling discussion on vegetation and soil changes that may shift under climate change. Methods (i.e. descriptions of scenarios) are scattered throughout this paragraph, and also through various sections of the Introduction. These should be moved to the Methods section.

\*\*\*\*\*AC: We have rewritten the introduction in response to the reviewer’s suggestions. The order of presentation has been changed so the three aspects of this study: vegetation, soil and climate change, are dealt with sequentially. The basins are referred to by name as are the biomes in each.

The manner in which the eight “treatment” cases are referred to have been made consistent throughout the paper, and we have tried to increase the clarity by more frequent reference to the case designators.

We have gathered various statements referring to the methodology from the manuscript and captions into one coherent Methods section on the recommendation of the reviewer.

Figures and Tables have been revised to be consistent with terms and groupings and order of presentation. Figure legends now use the same designators in the same order replacing several different orders and formats.

-The last sentence in the first paragraph (line 49) of the paper “Vegetation changes can alter soil properties.” is out of place and probably belongs in the first sentence of a paragraph on this topic.

\*\*\*\*\*AC: Addressed in the rewrite. This is now the topic sentence for the third paragraph in the Introduction.

-Second paragraph (line 50), suggest moving the second sentence as the opening sentence of the paragraph. This paragraph also jumps around a lot, and needs reorganizing.

\*\*\*\*\*AC: Addressed in the rewrite.

-Third paragraph of the paper (line 61) is disjointed. Can you incorporate these ideas into the paragraphs above?

\*\*\*\*\*AC: Addressed in the rewrite.

-Fourth paragraph, this part of the paper you are trying to make an argument for why you use the delta method on your historical observations, but it isn't clear. You talk about noise (line 70). What do you mean by this? This whole argument needs to be clearer and emerge from an explanation of what you have done. Right now it seems out of place.

\*\*\*\*\*AC: Addressed in the rewrite.

-Line 80, fifth paragraph. This is a strange paragraph. Of course, there have been lots of studies on climate change on hydrology and on mountain hydrology. Is it necessary? Are you planning on summing up all of the results in the field? I think you want to make the argument that lots of these studies have been done but most are missing the vegetation / soil / land surface change component. Perhaps rethink this approach and place your argument in that context.

\*\*\*\*\*AC: Addressed in the rewrite.

-Line 90-115. These are almost methods to me. I don't think this text belongs in the Introduction section.

\*\*\*\*\*AC: **Moved to the new Methods section.**

-Because you gloss over some things, the paper is difficult to follow. For example, you don't really describe the model so all the figures are tough to follow. What is "drift in"? You show this in the figures but it isn't explained (or I missed it). I think this is because you have not really described the model in the paper. I think you need to describe some bare minimum so the reader can follow your results.

\*\*\*\*\*AC: **Addressed in the rewrite. We have made a large number of changes in the use of terminology so that it is consistent and does not include unnecessary synonyms that could confuse the reader. This should make the text, which we appreciate is complex, more clear.**

-Figure 1. Should this be Figure 1? I think this figure belongs in methods, not in the Intro.

\*\*\*\*\*AC: **The reviewer is correct. This Figure has been placed in the Methods section.**

-Line 132. You barely describe the data input used to parameterize the model. I think you need some more detail here on what you did. Or, perhaps these sections need reorganizing so it is more clear what was done.

\*\*\*\*\*AC: **Addressed in the rewrite. We have rewritten this section and added more details and references to both the data and modelling strategy that have been published separately.**

-Line 146. What do you mean by "allow differentiation"?

\*\*\*\*\*AC: **Addressed in the rewrite. See lines 145 – 155 in the revised manuscript.**

-Line 150. This sentence starting with These CHRM models: : : is unnecessary and can be removed.

\*\*\*\*\*AC: **Removed.**

-Line 154. HRU have different sizes. This is an awkward sentence. Is it necessary?

\*\*\*\*\*AC: **Removed.**

-Line 156-164. This is a really important section to be clear, and it is not. I don't understand what you did, how you modified the HRUs for each scenario, and that is kind of the main point of the paper. I would suggest rewriting this paragraph.

\*\*\*\*\*AC: This text was rewritten so the changes that were made to the HRU's were made clear. The entire paragraph was rewritten. See lines 163 – 167 in the revised manuscript.

-Line 170. Global climate models

\*\*\*\*\*AC: “general circulation models” was replaced with “global climate models”

-Line 176. You start using your notation before you have explained it.

\*\*\*\*\*AC: Addressed in the revision. We have used a simplified notation that only covers what was changed in a specific case. We have also added text that specifically states the cases and columns have been added to tables to include the notation, and the same notation is used in the legends of figures. Also, the order has been made consistent throughout so the reader can follow it more easily.

-Section 2.1 and end of Section 2.4. I would strongly suggest you rethink how you are notating the paper's findings. You use so many acronyms that make it really difficult to read the paper. Could you think about using actual words for these acronyms? Perhaps Wolf, Marmot and Reynolds for the study sites? The same comment applies for your scenarios. You also use groups in two ways (I think). So, now you have a, b, c in the figures. On top of the CVS\_ /CSV, etc notation. It is a complex study to follow to begin with, so you need to make it easier for the reader (and the reviewers!) to follow.

\*\*\*\*\*AC: We now use Wolf Creek, Marmot Creek, and Reynolds Mountain in the text instead of acronyms.

We have used a simplified notation that only covers what was changed in a specific case using  $\Delta C$  for changed climate,  $\Delta V$  for changed vegetation,  $\Delta S$  for changed soil and the other permutations to cover the eight cases. We now refer to these as cases and not scenarios to avoid confusing the reader with SRES scenarios and RCPs.

All the text in both sections improved and the indices in the text were retained parenthetically for easier reading of the text. All of the related figures were revised to address these comments.

-Line 208 each other's effects. You use this personification a few times in the paper and it is odd.

\*\*\*\*\*AC: The text now avoids personification.

-Figure 2, I think you have the space here to just label the three sites in the Figure.

\*\*\*\*\*AC: We now use Wolf Creek, Marmot Creek, and Reynolds Mountain in the Figures instead of acronyms.

-Discussion, first paragraph, is too long. Break it up to make it easier to digest/understand/follow.

\*\*\*\*\*AC: Addressed in the revision. The text was broken into logical sections.

-Line 491, “: : such as RME where changes are complex and nonlinear: :

\*\*\*\*\*AC: Addressed in the revision.

-Table 3, needs to be organized. Can you add in lines/cells?

\*\*\*\*\*AC: Table 3 was revised to improve the organization. Space was added between the basins

### General

-I don't think you make the argument well for changing soils under climate change. This is an important argument to make strongly to support the need for the level of detail in the results. Suggest looking carefully at this.

\*\*\*\*\*AC: Addressed in the revision. We agree that this is an important component of the story and tried to make the explanation and the uncertainties in this clear.

See lines 159 – 167 in the revised manuscript.

-The initial paragraph of the paper, and some sections of the paper (Discussion, paragraph 1, line 478-509!) have extremely long paragraphs. These should be shorted and broken up. Try to think about the main point you want to make in a paragraph, and let that lead your writing.

\*\*\*\*\*AC: Addressed in the revision. Paragraphs length has been considered carefully in the revision and where possible different topics or subtopics separated to reduce paragraph length.

-Would you consider using a first person voice for this text? I wonder if it might help with some of the awkwardness of the text.

\*\*\*\*\*AC: We understand that there is nothing wrong with using first-person voice. All three co-authors, however, prefer to use passive voice style for scientific writing.

-This paper is really long. Suggest to think about all the figures, tables, and the results section (which is ~15 pages) and see where you could reduce the text? Think about each sentence you use and ask yourself if the reader needs to know this information? Why is it important? Can I be more clear? What could be moved to a Supplement section?

\*\*\*\*\*AC: This was addressed in the revision. We removed one of the figures and the text related to it. In other places we have simplified the presentation. We have added information that a reader should have to be able to better understand the presentation and the study. We have also referenced

our 2019 paper, upon which this paper builds, so a reader could seek more details that are provided therein.

-I am happy to review this paper again and get to some of the details once the paper has been reorganized and these comments addressed.

\*\*\*\*\*AC: Thank you for your insightful and detailed comments which were accepted and have been most useful in improving the manuscript.

**Referee #2**

The paper addresses a very relevant topic with high scientific and applied implications. Used methodology is robust and results of high interest. However, I agree with reviewer 1 that the paper is very difficult to be read because of excessive information on the one side, and because current structure is currently unclear. I think it is necessary to select more the information and to facilitate to readers the lecture. Once this will be achieved, it will be a great contribution for the Journal and most important to the field of mountain hydrology.

\*\*\*\*\*AC: We have rewritten the manuscript to make the presentation of a complex study easier to follow. The structure of the manuscript has been simplified and the terminology changed to a simpler and more consistent form. We have modified most of the figures to improve clarity and consistency of the presentation.

Specific comments.

-The abstract is not very informative now, it does not inform about the sign and magnitude of predicted changes.

\*\*\*\*\*AC: Addressed in the revision. Extraneous material has been removed and the focus placed on describing the simulated effects of changes in climate, vegetation, and soils.

-Line 9. I would not say "seldom studied" Impact of climate-vegetation changes on hydrology have been widely studied in many areas; the most novel of the study is to focus on snow dominated basins.

\*\*\*\*\*AC: Addressed in the revision. We have emphasized that the novel aspect of this study is snow dominated mountain basins. See line 9 in the revised manuscript.

-Line 14. Not sure if "but" is appropriate here. I would say ...SWE "and" increased evapotranspiration.

\*\*\*\*\*AC: The word "but" was changed to "and".

-Line 16. It is not stated before that soils have been also perturbed.

\*\*\*\*\*AC: Addressed in the revision. Text regarding soils in the Introduction has been rewritten and made clear.

- Introduction needs better organized. The literature review are mixed with the objectives. I would detail the objectives at the end of the section.

\*\*\*\*\*AC: Addressed in the revision.

- Paragraph in lines 45-50 needs to be better organized.

\*\*\*\*\*AC: Addressed in the revision.

-Lines 57-60 are highly repeated with previous paragraph.

\*\*\*\*\*AC: Addressed in the revision.

-Lines 65-80 can be moved to methodology. - Can you incorporate in Figure 1 the applied changes to soils?

\*\*\*\*\*AC: Addressed in the revision. The text was moved to the Methods section, and the changes applied to the soils have been added to Figure 2 [previously Figure 1].

- Line 157- "changed" instead of "changes".

\*\*\*\*\*AC: Corrected.

- I would convert lines 185-200 into a table. -Section 2.3. Did you perturb T and P, or all the variables?

\*\*\*\*\*AC: Thanks for this excellent suggestion. We changed these lines into the new Table 2.

We did perturb P and T and kept relative humidity constant to allow vapour pressure to change with warming. Text was added to the method to make the reader aware of this fact. Also, we note in the text that no change were assumed in the rest of the parameters such as wind as the RCM outputs for these variables were highly uncertain for the present climate.

- Figure 1 is absolutely necessary to understand methodology, may be you can use a similar template to provide a fast view of the most important hydrological changes at each site and under different environmental changes.

\*\*\*\*\*AC: In Figure 2 [formerly Figure 1] we added the modelled change in the snow water equivalent (SWE) under climate change scenario into Figure 2. Because we have eight scenarios, including the present climate-vegetation-soil, and six parameters for each scenario (Peak SWE, timings, annual runoff, etc.), it is not easy to show the results on a figure similar to Figure 1.

- Many parts of Results are in reality discussion. I would separate better the contents or I would create a results and discussion section.

\*\*\*\*\*AC: Addressed in the revision. Discussion text has been moved from the Results to the Discussion.



-Line 219. Turkey's test should be presented in Methods section.

\*\*\*\*\*AC: Addressed in the revision. A new paragraph was added to the Methods to describe the test. See lines 195 - 204 in the revised manuscript.

-Line 298. It is interesting to see snow cover insensitive to vegetation when many studies point out the opposite.

\*\*\*\*\*AC: We have emphasized this more strongly in the revision.

- I do not see the point of a section 3.2 about snow characteristics when 3.1 also presents changes on snow.

\*\*\*\*\*AC: We are of the opinion that these two sections cover very different aspects and chose not to combine them so as to bring out important results.

- Are the hypsometry of the three catchments similar or different? how this may affect the results?.

\*\*\*\*\*AC: We have shown range of elevation and other physiographic characteristics of the basins in Figure 2 and we discussed the similarities and differences between the basins, which are provided in section 2.1 Study areas and data sources. We acknowledge that there might be some uncertainties in the results due to the different characteristics of the basins, but they are the classic basins for their regions and so we have to use what nature has provided and what research organisations have instrumented.

We have work in progress on the impact of hypsometry that will further address the reviewer's point.

- MCRB is the only with predicted deforestation; is this the reason why snow is the most resilient to CC? - Are normal the very low values of sublimation in WC and RC?

\*\*\*\*\*AC: We also expect deforestation in Reynolds Mountain as shown in Figure 2 (lower panel) where sage replaces different types of trees.

- Are normal the very low values of sublimation in WC and RC?

\*\*\*\*\*AC: We have not modified the manuscript in response to this comment, but higher elevations in Marmot Creek are very cold and snowcover period is longer there and a moderate warming does not affect the snow at these elevations (Rasouli et al., 2019a), but it does affect snow at low elevations similar to the deforestation effect.

Total annual sublimation to some extent depends on the annual snowfall and peak SWE. We have less snowpack in Wolf Creek, so we expect lower sublimation in Wolf Creek over an annual cycle and large sublimation in Marmot Creek as it has the highest snow accumulation among the three sites and is subject to Chinook winds.

-I hope my comments will result useful when preparing the revised manuscript.

\*\*\*\*\*AC: We appreciate your very helpful comments. Addressing your comments and suggestion has helped us prepare a much improved revision.

# Are the effects of vegetation and soil changes as important as climate change impacts on hydrological processes?

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**Abstract.** Hydrological processes are widely understood to be sensitive to changes in climate, but the effects of **concomitant** changes in vegetation and soils have seldom been considered **in snow dominated mountain basins**. The response of mountain hydrology to **vegetation/soil changes in the present and a future climate** was modelled in three snowmelt dominated mountain basins in the North American Cordillera. Cold regions hydrological models developed for each basin **using current and expected changes to vegetation and soil parameters** were driven with recent and perturbed high altitude meteorological observations. Monthly perturbations were calculated using the differences in outputs between the present and a future climate scenario from eleven regional climate models. In the three basins, future climate change alone decreased the modelled peak snow water equivalent (SWE) by 11-47% and increased the modelled evapotranspiration by 14-20%. However, including future changes in vegetation and soil for each basin changed or reversed these climate change outcomes. In Wolf Creek in the Yukon Territory, Canada a statistically insignificant increase in SWE due to vegetation increase in the alpine zone was found to offset the statistically significant decrease in SWE due to climate change. In Marmot Creek in the Canadian Rockies, the increase in annual runoff due to the combined effect of soil and climate change was statistically significant while their individual effects were not. In the relatively warmer Reynolds Mountain in Idaho, USA, vegetation change alone decreases annual runoff volume by 8%, but changes in soil, climate, or both do not affect runoff. At high elevations in Wolf and Marmot creeks, the model results indicated that vegetation/soil changes moderated the impact of climate change on peak SWE, the timing of peak SWE, evapotranspiration, and annual runoff volume. However, at medium elevations, these changes intensified the impact of climate change, further decreasing peak SWE and sublimation. The hydrological impacts of changes in climate, vegetation, and soil in mountain environments were similar in magnitude but not consistent in direction for all biomes; in some combinations, this resulted in enhanced impacts at lower elevations and latitudes and moderated impacts at higher elevations and latitudes.

## 1 Introduction

Under warmer, **less snowy climates, vegetation and soil properties are** expected to change, which will result in evapotranspiration increases (Beniston, 2003) and shifts in runoff patterns (Neilson and Marks, 1994). Vegetation response to warming varies with climate (Stow et al., 2004). Deforestation, afforestation, and disturbance in the vegetation composition are other mechanisms that have widely changed the vegetation cover, especially in mountainous environments. Bosch and Hewlett (1982) reviewed the impacts of deforestation and afforestation on water yield in forested landscapes and concluded that water yield increases in

35 coniferous forests (e.g., pine), deciduous hardwood forests, and shrubs by a reduction in cover. Studies also show that the growth rates of trees have increased (Innes, 1991), the forest composition (e.g., in the Pacific Northwest) has changed (Dale and Franklin, 1989), and tree-line has moved vertically and Northwards in the last century (Hansell et al., 1971). The major drivers of vegetation change in western North America are climate, mountain pine beetle, logging, and wildfires (Macias-Fauria and Johnson, 2009; Halofsky et al., 2018).

40 At northern latitudes, where the air temperature is low, the growing season is short, cloud cover is persistent, and the solar angle is small, the vegetation composition responds quickly to changes in climate and nutrient availability; with warming, rapid changes in thawing and freezing processes (Zhang et al., 2008; Walvoord and Kurylyk, 2016), snowmelt rates, and soil moisture (Bales et al., 2011) are expected. One example of how the interaction between climate and vegetation can change ecosystems is the expansion of shrubs in northern latitudes (Martin et al., 2017; Myers-Smith and Hik, 2018). Warming degrades permafrost in northern mountains and leads to shrub tundra expansion (Tape et al., 2006; Hallinger et al., 2010). Increased shrub coverage traps more windblown snow, increases snowmelt volumes, lowers spring albedo, and alters melt rates (Pomeroy et al., 2006; Krogh and Pomeroy, 2018). Warming has also resulted in increases in the height of the tundra community (Bjorkman et al., 2018). Many mountain plants begin growth at near-freezing temperatures when snowpacks start to melt (Billings and Bliss, 1959), and snow depth and snowmelt rates affect vegetation composition (Billings and Bliss, 1959; Stanton et al., 1994). In a warmer climate, the abundance of cold-adapted species decreases and warmth-demanding vegetation expands into higher elevations (Lamprecht et al., 2018) and plant communities shift to more northern latitudes (Alberta Natural Regions Committee, 2006; Schneider et al., 2009; Mann et al., 2012; Schneider, 2013; Myers-Smith and Hik, 2018).

55 Changes in vegetation can lead to changes in soil properties and important local and global feedbacks in ecohydrological processes and energy budgets (Osterkamp et al., 2009; Rawlins et al., 2009). Soil development, however, may not occur as quickly as vegetation change (Innes, 1991) and soil properties may vary from the initial phase of the colonization of the bare surface to the establishment of a forest (Crocker and Major, 1955). In cold regions in general, and mountains in particular, the amount and timing of snowmelt affects vegetation type, soil moisture, nutrient transport, soil and leaf temperature, surface microclimate, and growing season (Billings and Bliss, 1959; Walker et al., 1993; Stanton et al., 1994, Callaghan et al., 2011). Potential changes in soil, especially changes in organic matter content can have important effects on soil moisture, permafrost, infiltration, groundwater recharge, and runoff processes as climate, hydrology, and vegetation change (DeBano, 1991; DeFries and Eshleman, 2004; Osterkamp et al., 2009). Deforestation increases soil bulk density and decreases soil porosity, both of which alter infiltration, percolation, aeration, and erodibility (Reiners et al., 1994). Increased active layer thickness over permafrost, as a result of the warming climate, allows more subsurface water storage, higher nutrient transport, and a deeper root zone, which is favourable for shrub expansion (Sturm et al., 2005). Because they are interrelated but have an uncertain timing, it is important to consider separately and together the climate, vegetation, and soil changes that may occur in future.

65 Simulations of future hydrological conditions in mountains are challenging because of the large biases between climate model outputs and locally observed hydroclimatic conditions and the seasonal nature of snow accumulation and depletion (Fowler et al., 2007; Bennett et al., 2012). In the climate perturbation method, also known as the delta change factor method, (e.g., Rasouli et al., 2014, 2015), observations are perturbed using the difference (delta) between modelled present and future climates. This method avoids the computational cost of the dynamical downscaling and maintains consistency in relationships of the atmospheric fields, which may be distorted in statistical methods if the interaction of the variables is not considered (Hijmans et al., 2005; Gutmann

70 et al., 2016). Unlike using the RCM outputs directly, the perturbation approach produces spatial and seasonal precipitation patterns based on observations, with the changes due to differences between present and future simulated climate (Hay et al., 2000; Kay et al., 2009; Sunyer et al., 2012). This represents weather with reasonable accuracy and also represents observed extremes such as dry periods and storms. Of particular importance for mountain hydrology are that the dynamics of precipitation, its phase, and its increase with elevation are represented realistically. Limitations of applying monthly climatological change factors to perturb the climate are that any future changes in large-scale weather patterns and their impact on extremes, and sequences of wet or dry spans are not adequately represented. This is similar to the assumption of stationarity in the relationships between large-scale circulations and locally observed data that are made in statistical downscaling. Changes in synoptic dynamics of the atmosphere cannot be captured by the climate perturbation method, nor can RCMs capture local-scale processes in mountainous regions (Rasouli, 2017).

75 There have been many studies on the impact of climate change on hydrology and some on mountain hydrology (e.g. Link et al. (2004); Flerchinger et al. (2012); Fang et al. (2013); Pomeroy et al. (2003, 2012, 2015); Rasouli et al. (2014); Williams et al. (2015)). The present study builds on recent understanding of the impact of climate perturbations on three headwater basins in the North American Cordillera where future reduced snowfall amounts are offset by reduced losses due to snow sublimation and increased rainfall amounts are offset by increased evapotranspiration, together leading to insignificant changes in annual runoff (Rasouli et al. 2019a). But, there are fewer studies that focus on the impacts of land surface changes on mountain hydrology. In most impact studies, changes in vegetation, soil, and land surface are not well represented, and there is limited knowledge about how the combination of climate, vegetation, and soil changes impacts hydrological processes and basin level discharge (Brown et al., 2005).

85 Interactions between climate, vegetation, and soils are complex (Rodriguez-Iturbe, 2000) and the time lag between vegetation response to climate changes and soil response to climate and vegetation changes is unclear (Innes, 1991). In a warmer climate, with a longer snow-free season, and increased precipitation in northern latitudes, vegetation is expected to increase where adequate soil moisture and nutrients permit. Therefore, assuming there will be no change in vegetation in future climates introduces uncertainty and possible errors in hydrological impact studies of climate change. Modelling climate change effects on hydrology with and without vegetation and soil changes can help to understand the separate and combined effects of climate, vegetation, and soil changes in mountainous headwater basins. Rasouli et al. (2019a) show that future climates are warmer and wetter, especially in the northern latitudes, and that temperature and precipitation changes have complex effects in snow-dominated watersheds. Warmer and wetter future conditions are expected to drive vegetation, soil, and hydrological changes, but such changes have not been thoroughly studied. The objective of this study is to investigate the hydrological changes due to climate perturbations, building on Rasouli et al. (2019a), and plausible concomitant soil and vegetation changes, adapted from Alberta Natural Regions Committee (2006); Schneider et al. (2009); and Myers-Smith and Hik (2018) for three instrumented headwater basins ranging from middle to high latitudes in the North American Cordillera.

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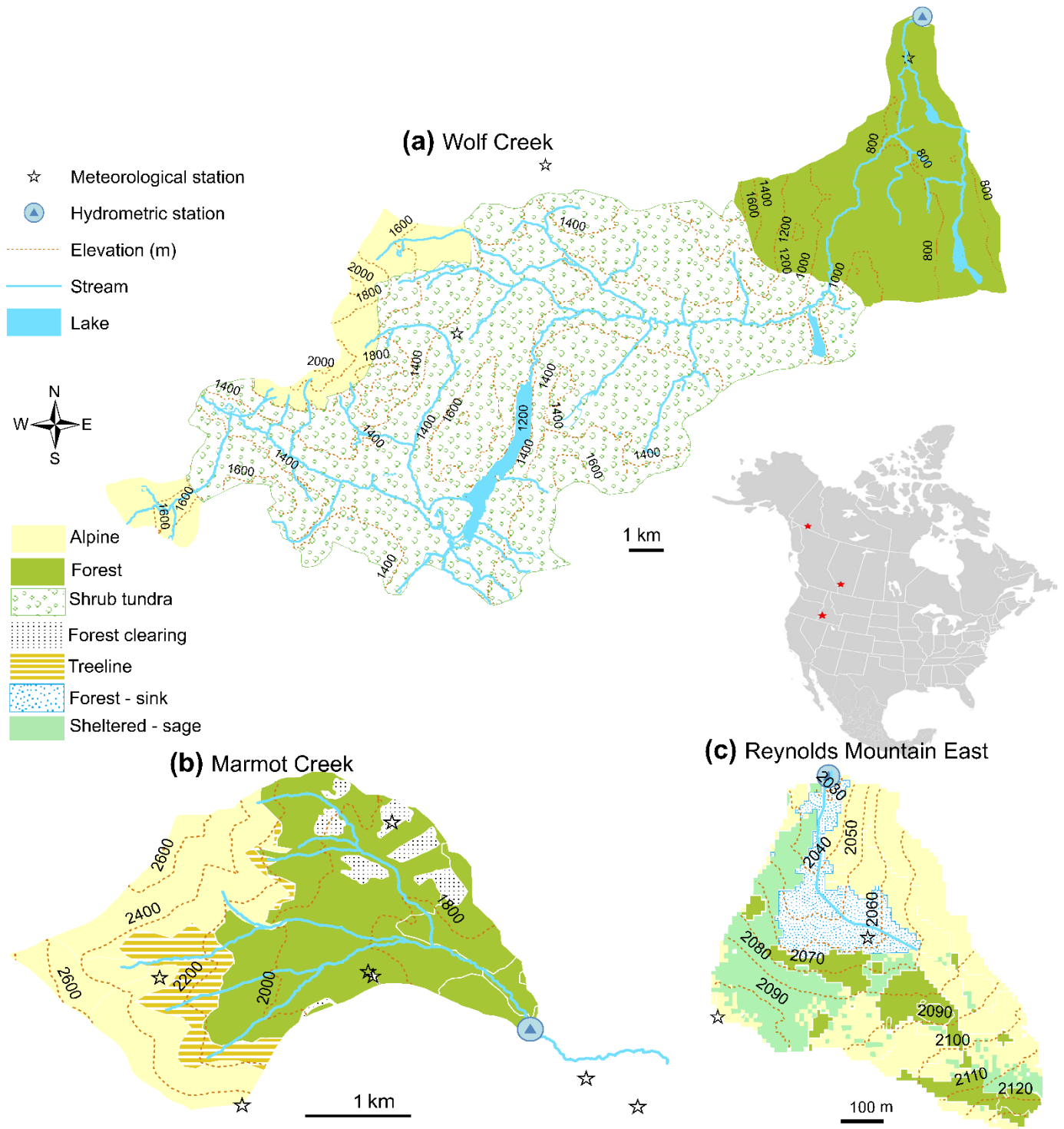
## 2 Methods

### 2.1 Study sites and data sources

105 Three mountain basins ranging from middle to high latitudes in the North American Cordillera are examined: a sub-Arctic basin (Wolf Creek Research Basin ~61°N, Yukon Territory, Canada), a headwater catchment in the Canadian Rockies (Marmot Creek Research Basin, ~51°N, Alberta, Canada), and a small catchment with cool montane climate (Reynolds Mountain East catchment, hereafter called Reynolds Mountain, ~43°N, Idaho, USA) (Fig. 2). All three basins are located in transition climate zones based on climate classification (Köppen 1936). Wolf Creek has the shortest distance to the Pacific Ocean (Figure 1), lowest average elevation, coldest climate, and lowest annual precipitation amongst the three basins. Marmot Creek has the highest elevation, largest elevation range and highest annual precipitation and wind speed. Reynolds Mountain has the smallest drainage area, highest average elevation, and lowest wind speed (Table 1).

110 Jack pine, spruce, and aspen forests are dominant vegetation types at low elevations in Wolf Creek (Francis et al., 1998) and 65% of the basin area above the forest biome is covered with birch and willow shrub tundra with heights ranging between 30 cm to 2 m. Alpine tundra with short moss, grass, and bare rock covers high elevations in Wolf Creek. Engelmann spruce and subalpine fir cover high elevations and lodgepole pine stands cover low elevations in Marmot Creek (Kirby and Ogilvie, 1969). Areas adjacent to the treeline in Marmot Creek are covered with shrubs and alpine larch. The alpine zone is composed of grass, moss and large areas of bare rock. The spatial variability of vegetation is large within Reynolds Mountain (Seyfried et al., 2009; Winstral and Marks, 2014) and grass, mountain sagebrush, riparian willow, aspen, and coniferous trees are dominant vegetation types in this basin. Almost 43 % of Wolf Creek is covered by continuous and discontinuous permafrost (Lewkowicz and Ednie, 2004).  
120 Soils do not freeze in Reynolds Mountain and freeze seasonally in Marmot Creek.

Precipitation was measured by tipping bucket rain-gauge, and unshielded “BC style standpipe”, and Nipher-shielded storage gauges in Wolf Creek, by an Alter-shielded Geonor storage gauge in Marmot Creek, and by shielded and unshielded storage gauges in Reynolds Mountain. Snowfall observations were adjusted using wind undercatch correction equations (Goodison et al., 1998; Smith, 2009) based on wind-shield and wind speeds measured at gauge height. Air temperature, humidity, wind speed, shortwave radiation, and streamflow were measured and stored at hourly time steps for each basin. Suitable driving meteorological time series from these observations were available for 1993-2011 in Wolf Creek, 2005-2014 in Marmot Creek, and 1983-2008 in Reynolds Mountain. Long-term datasets and descriptions of the variables for each basin were published by Reba et al. (2011), Fang et al. (2019), and Rasouli et al. (2019b).



**Figure 1.** Vegetation, hydrography, topography, and meteorological stations of the three headwater study basins: (a) Wolf Creek Research Basin, Yukon Territory, Canada; (b) Marmot Creek Research Basin, Alberta, Canada; and (c) Reynolds Mountain within Reynolds Creek Experimental Watershed, Idaho, USA.

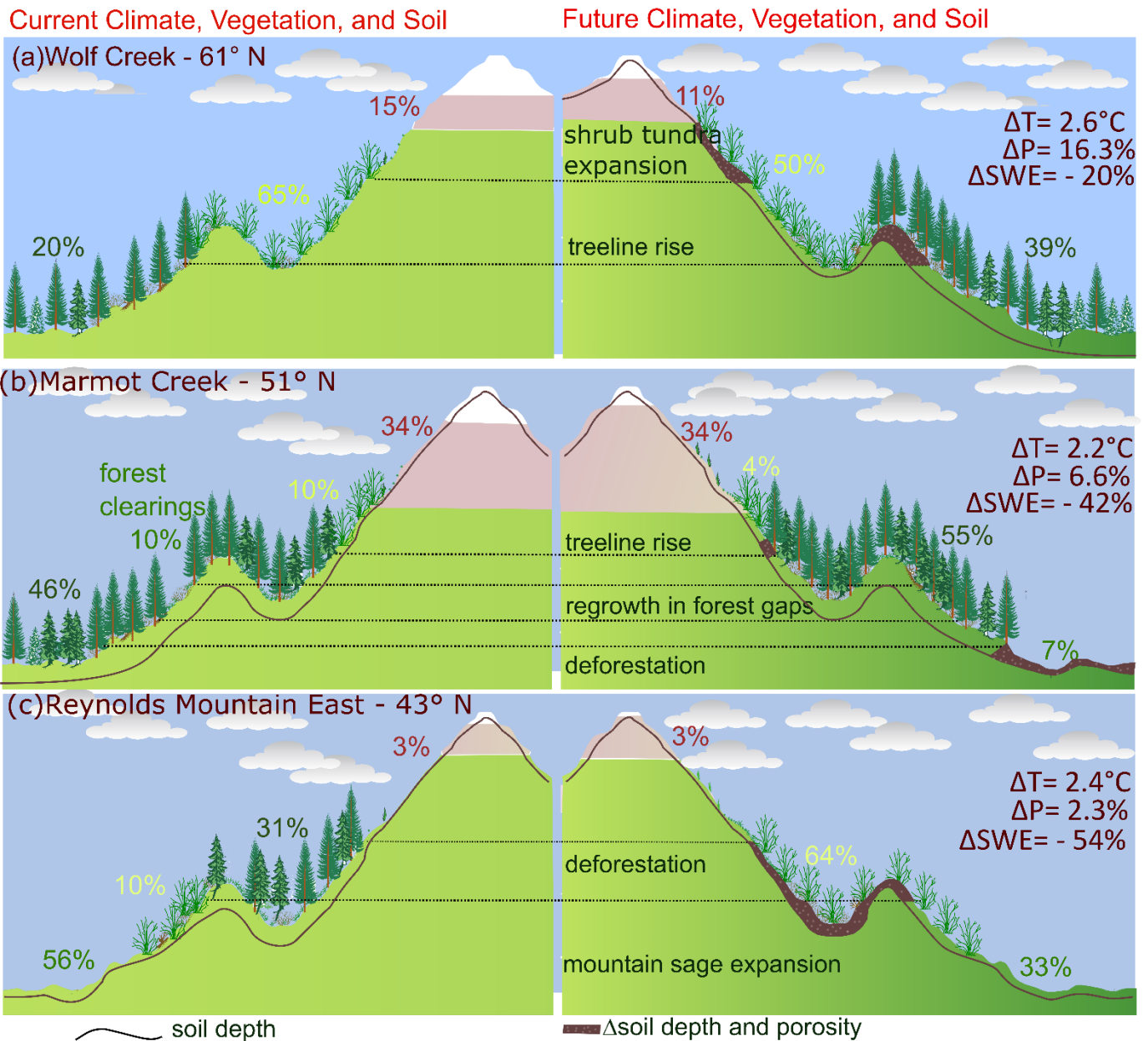
## 2.2 Modelling strategy

135 As described in Rasouli et al. (2019a), a distinctive distributed hydrological model for each basin was developed on the Cold  
Regions Hydrological Modelling platform (CRHM – Pomeroy et al., 2007). The models represent the major hydrological  
mechanisms in cold regions and found in these basins, including snow transport and redistribution by wind, snow interception,  
snow sublimation, sub-canopy radiation, energy balance snowmelt, mass and energy balance evapotranspiration, infiltration, and  
140 runoff over frozen and unfrozen soils (e.g., Pomeroy et al., 1999; MacDonald et al., 2009). Parameters for modelling each  
hydrological process were obtained from field measurements in the basins or similar basins following the deduction-induction-  
abduction approach outlined by Pomeroy et al. (2013). The models were discretized into hydrological response units (HRUs) that  
are spatially segregated based on hydrological function and parameter as defined by vegetation type, elevation, slope and aspect,  
soil depth, soil layers, hydrography, and the variability of basin attributes. The CRHM models were run at hourly time steps (Table  
1). Details on model parametrization and performance are available in Rasouli et al. (2014, 2015) and Rasouli (2017).

145 Eight change cases were used to differentiate the individual and combined effects of changes in climate ( $\Delta C$ ), vegetation ( $\Delta V$ ),  
and soils ( $\Delta S$ ) from the present conditions (base case). The vegetation and soil changes applied are conceptualized in Figure 2 and  
summarized in Table 2. The effects of vegetation and soil changes on snow regimes and hydrological variables were evaluated  
under conditions in which: (1) climate does not change, but vegetation/soil changes occur ( $\Delta VS$ ), (2) climatic conditions change  
but no changes in future vegetation and/or soil occur ( $\Delta C$ ), and (3) changes in future climate will be accompanied by vegetation  
150 and soil changes ( $\Delta CV$ ,  $\Delta CS$ , and  $\Delta CVS$ ). Porosity and soil depth are expected to change as a result of vegetation and climate  
change. The specific vegetation and soil changes applied in each watershed were different based upon the current understanding  
of likely future terrestrial ecosystems in each of these three basins. In Wolf Creek, the vegetation changes were an upslope  
movement of the treeline and expansion of shrub tundra into former sparse tundra in response to a warmer and wetter climate  
(Figure 2a). In Marmot Creek, the changes were an upward movement of the treeline, afforestation of areas harvested in the 1970s  
155 and 1980s, and deforestation of the lower elevations due to fire and disease in a warmer climate (Figure 2b). In Reynolds Mountain,  
the changes were deforestation of all trees (aspen, fir, willow) and expansion of mountain sage due to a warmer climate with  
persistent water deficits. Other combinations of these vegetation changes in the three basins were explored to examine hydrological  
uncertainty due to various terrestrial ecosystem trajectories; they produced similar results and are not presented here. Changes in  
the organic layer of soils following vegetation changes can alter the soil characteristics, including soil macropores and hence, alter  
160 snowmelt/rainfall infiltration, thawing/freezing processes, recharge into groundwater, and runoff mechanisms. The soil porosity  
in different soil layers and soil depth were two soil model parameters that were changed to bring the changed soil characteristics  
in line with those currently associated with vegetation and land cover types (Figure 2).

Hydrological model parameters that represented the current vegetation cover and soil characteristics in forest, shrub tundra, grass,  
sage, and alpine tundra were determined using field measurements in each basin. To represent soil change and vegetation  
165 conversion from one type to another in the model, the area being converted was added to or subtracted from an existing HRU with  
that vegetation and soil type or parameters (vegetation, soil, or both) were modified in the converted HRUs. HRUs were altered  
to represent three different changes (i) only vegetation change, (ii) only soil change, and (iii) both vegetation and soil change.





170 **Figure 2.** Schematic illustration of the vegetation cover under base case and future climate, vegetation, and soil ( $\Delta CVS$ ) in Wolf Creek Research Basin, Marmot Creek Research Basin, and Reynolds Mountain. Dark shading indicates areas where changes to soil are expected in future. The numbers show the areal percentage of alpine, forest, shrub tundra, grassland, and forest clearing biomes.  $\Delta T$ ,  $\Delta P$ , and  $\Delta SWE$  are from Rasouli et al. (2019a).

### 2.3 Perturbed observations

175 Monthly perturbed climates were constructed from a downscaling method applying delta changes in monthly climatology to base case hourly meteorological observations from various elevations in the research basins; see Rasouli et al. (2019a) for details. The monthly perturbation was determined from the results of eleven regional climate models from the North American Regional

Climate Change Assessment Program (NARCCAP), which are driven by outputs from multiple global climate models (GCMs) for the A2 SRES emission scenario (Mearns et al., 2007). Using observed data modified by the monthly delta gives an estimate of the potential climate change impacts on these driving forces consistent with the large-scale atmospheric circulations. The deltas used were the difference between the simulated current monthly 30-year climatology (1971–2000) and the future (2041–2070) monthly 30-year climatology (2041–2070) for 11 RCMs (Rasouli et al., 2019a).

## 2.4 Significance testing

Significant changes and differences in water balance components, snow characteristics, and their timing (initiation date, peak SWE date, snow-free date, and duration of snowcover season) between simulations under the present period (base case) and simulations under different cases of changes in climate ( $\Delta C$ ), vegetation ( $\Delta V$ ), and soil ( $\Delta S$ ) were assessed with the nonparametric Mann–Whitney U-test (Wilcoxon, 1945; Mann and Whitney, 1947). The differences between simulated distributions in the modelled present period for  $n$  years ( $x_{1:11 \times n}^c, 11 \times n$  values) and the simulated distributions in the modelled future periods, obtained for eleven RCMs ( $x_{1:11 \times n}^f, 11 \times n$  years) were determined (18 for Wolf Creek, 8 for Marmot Creek, 25 for Reynolds Mountain). Assessment of the changes in the hourly SWE distribution due to vegetation changes was done with the nonparametric two-sample Kolmogorov-Smirnov test (Massey, 1951). This test evaluates the difference between the cumulative density functions of the hourly SWE in the present period and a climate or vegetation alternative. The confidence interval in plots is based upon the standard deviation of the results for the 11 RCMs and the years of observations in each watershed.

## 2.5 The honestly significant difference test

An analysis of variance (ANOVA) was used to determine if there is a case that is different from the others. This test, however, does not provide information on the pattern of differences between the means of the eight cases (Table 2). The honestly significant difference test (Tukey 1991) is widely used test to analyze the pattern of difference between means using pairwise comparisons. In the pairwise comparisons, the significant difference between a pair of means is determined using a statistical distribution that gives the exact sampling distribution of the largest difference between a set of means originating from the same population (Abdi and Williams, 2010). In this test, groups that are statistically different based upon paired comparison are labelled “a”, “b”, etc., ordered by mean from lowest to highest, are formed. Using an analysis of variance on the annual differences between the modelled future and the modelled base case and the honestly significant difference test for each basin, differences in snow and runoff under the four groups of the eight cases were determined (Table 2).

## 3 Results

### 3.1 Synergic effects of climate, vegetation, and soil changes on snow and runoff regimes

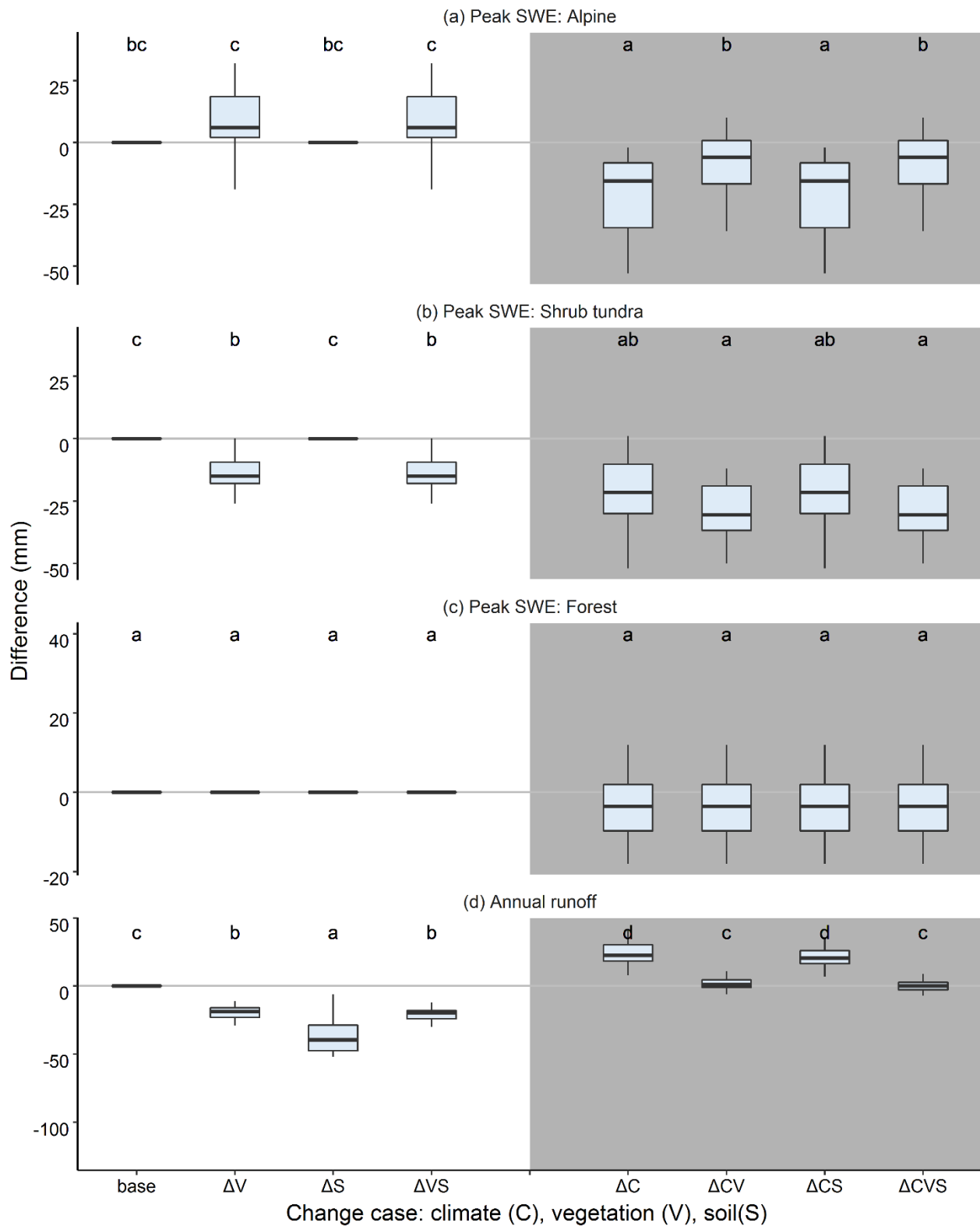
Changes in simulated peak SWE and annual runoff volume due to vegetation, soil, and their interaction in the present climate ( $\Delta V$ ,  $\Delta S$ , and  $\Delta VS$ ) were compared with the modelled present (base case; no changes in climate, vegetation, and soil) to determine the effect of individual or combined changes. Similarly, changes in simulated peak SWE and runoff due to changes in vegetation,

soil, and their interaction in the future climate were compared with future-climate **change** as well as present-climate. In total, four **cases** under present the climate and four cases under the future climate were studied and statistical **differences**, based on the Tukey's honestly significant difference test, were distinguished from the modelled present, and all cases were classified into multiple groups for each variable (Fig. 3, 4 & 5).

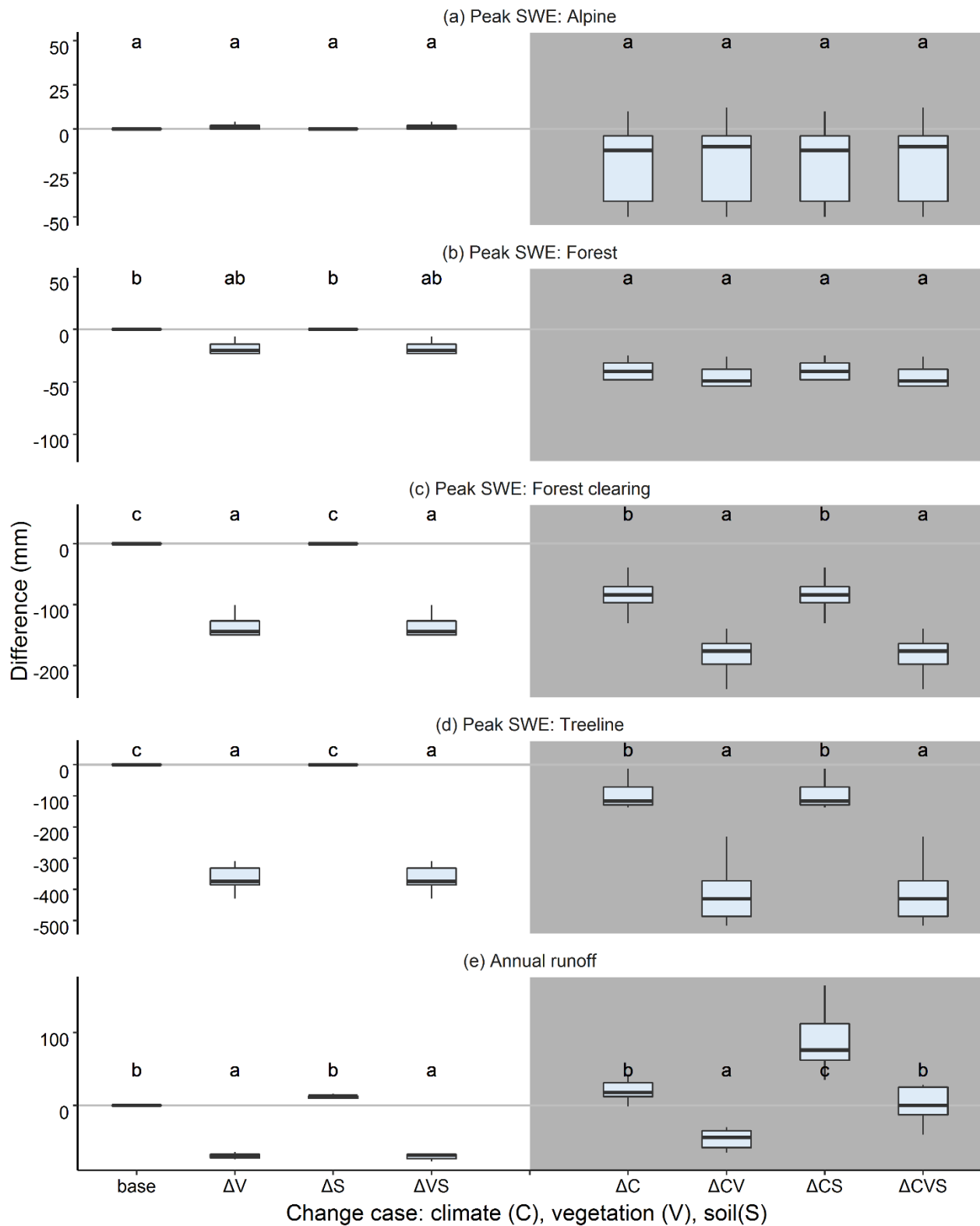
215 In Wolf Creek (Figure 3), the peak SWE declined significantly with  $\Delta C$  (group "a") in the alpine biome (Fig. 3a), and increased insignificantly with  $\Delta V$  and  $\Delta VS$  in the present climate. Peak SWE decreased significantly with  $\Delta C$ ,  $\Delta CV$ ,  $\Delta CS$ , and  $\Delta CVS$  (groups "a" and "b") in the shrub tundra biome (Fig. 3b), and did not change significantly with any combinations of vegetation and climate changes in the forest biome (all eight cases are in group "a") (Fig. 3c). In the alpine biome within Wolf Creek, the effect of increasing alpine vegetation on increasing peak SWE (Fig. 3a) is not statistically significant by itself, but was sufficient  
220 to offset the significant decrease in SWE from climate change. In contrast to the forest biome SWE in Wolf Creek, which is not affected by any changes (Fig. 3c), and to the alpine biome where combined changes counteracted each other, the decrease in peak SWE in the shrub tundra biome by climate change is intensified with concomitant vegetation change (Fig. 3b). Soil changes do not affect peak SWE in Wolf Creek. The annual runoff volume in Wolf Creek decreases significantly with  $\Delta V$ ,  $\Delta S$ , and  $\Delta VS$  change cases in the present climate and increases significantly for the future climate  $\Delta C$ , and  $\Delta CS$  cases (Fig. 3d). The decrease  
225 in annual runoff with soil and vegetation changes ( $\Delta V$ ,  $\Delta S$  and  $\Delta VS$ ) in the present climate (groups "a" and "b") is offset by the increases in runoff with climate change (group "d"), such that the combined effects of climate, vegetation and soil change ( $\Delta CV$  and  $\Delta CVS$ ) on runoff in Wolf Creek are not different from the base case of current conditions.

In Marmot Creek (Figure 4), the high elevation alpine biome peak SWE showed no significant response to vegetation and/or climate changes (all eight cases are in group "a", Fig. 4a). In the forest biome, peak SWE declines with climate change ( $\Delta C$ ), (group "a" vs. base case group "b", Fig. 4b). In the forest clearing and treeline biomes (Figure 4 d & e), there are significant decreases in peak SWE under  $\Delta V$  and  $\Delta VS$  and in the forest clearing also with climate changes and all case combinations (groups "a" and "b", Fig. 4c, Fig. 4d). Soil changes alone ( $\Delta S$ ) do not affect peak SWE in Marmot Creek. The annual runoff volume in Marmot Creek decreases with  $\Delta V$  and  $\Delta VS$  and increases with  $\Delta CS$  (Fig. 4e). This counteracting behavior is evident in the response of annual runoff to  $\Delta C$  and  $\Delta CVS$ , which is not significantly different from the base case (all are in group "b"). In  
230 contrast, the combined effect of climate and soil change ( $\Delta CS$  is "c" in Fig. 4e) is magnified from that of climate alone. Therefore, soil-climate interactions ( $\Delta CS$ ) are more important in changing annual runoff in Marmot Creek than the individual effects of soil and climate and are counteracted by concomitantly changing vegetation.

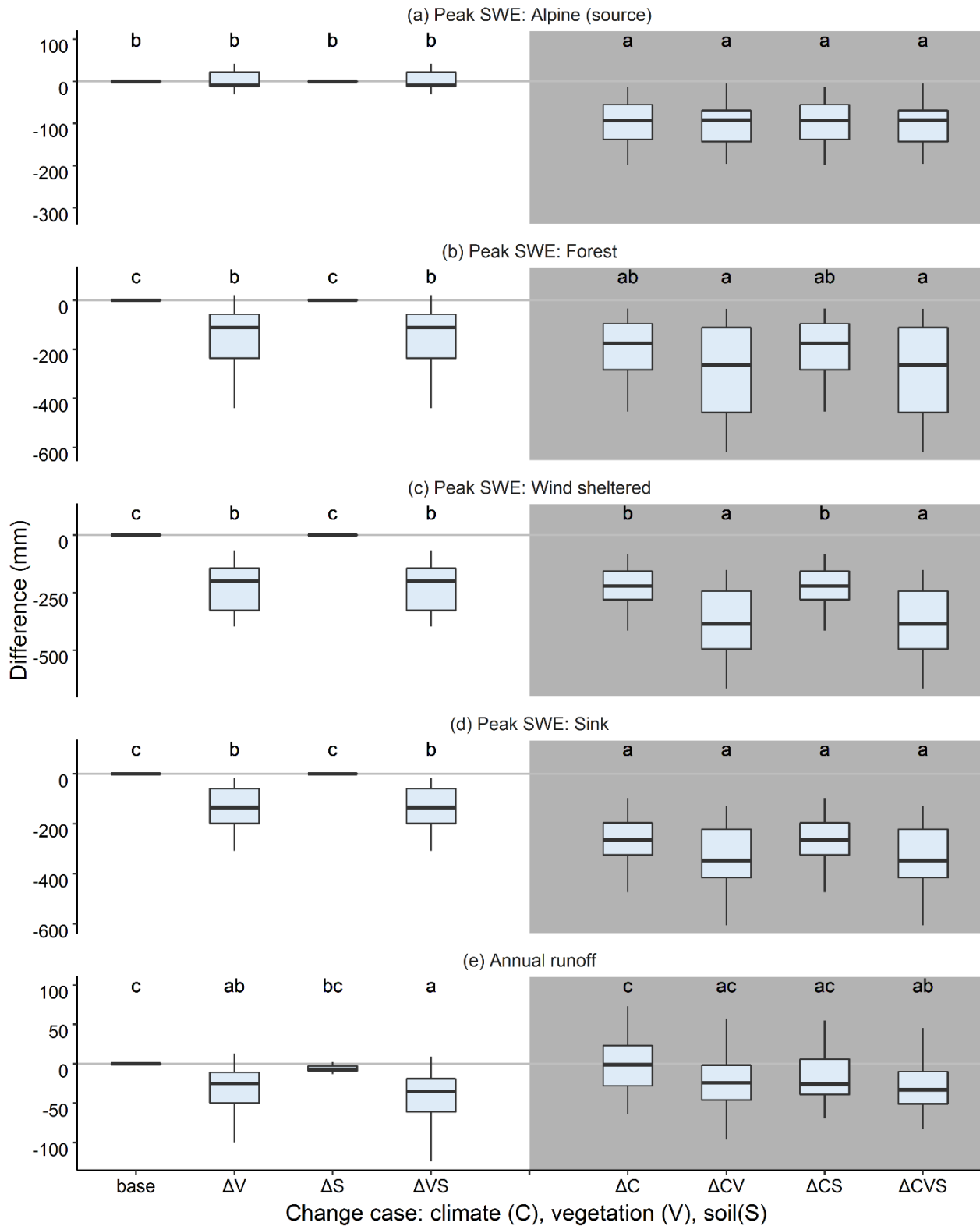
In Reynolds Mountain (Figure 5), the alpine biome peak SWE decreases significantly under climate change ( $\Delta C$ ) (group "a", Fig. 5a). Significant decreases in peak SWE occur with both vegetation and climate change (groups "a" and "b") in each of the forest biome (Fig. 5b), the blowing wind sheltered zone (Fig. 5c), and the blowing snow sink zone (Fig. 5d). The peak SWE in all of the biomes in Reynolds Mountain shows significant decreases under climate, vegetation, and the combination of these two (Fig. 5), except for the alpine biome, which shows a significant decrease only due to climate change (Fig. 5a). Similar to the other two basins, soil changes do not affect peak SWE in Reynolds Mountain. Climate ( $\Delta C$ ) and soil ( $\Delta CS$ ) changes do not affect the annual runoff volume whilst vegetation change and combined vegetation and soil change ( $\Delta V$  and  $\Delta VS$ ) significantly decrease annual  
240 runoff (Fig. 5e). Even though the individual effect of soil change on runoff is not statistically significant, its combined effect can enhance the effect of the vegetation change in diminishing annual runoff from this basin (Fig. 5e).



**Figure 3.** Differences in peak snow water equivalent (SWE) and annual runoff volume under seven combinations of changes in climate, vegetation, and soil in the Wolf Creek Research Basin relative to present climate, present vegetation, and present soil with no change (base). Lower case letters from Tukey's HSD test indicate groups that are significantly different from each other. The unshaded cases on the left-hand side of the plot demonstrate changes under modelled present climate, and the shaded cases on the right-hand side of the plot demonstrate vegetation and soil changes under modelled future climate cases.



**Figure 4.** Differences in peak snow water equivalent (SWE) and annual runoff volume under seven combinations of changes in climate, vegetation, and soil in the Marmot Creek Research Basin relative to present climate, present vegetation, and present soil with no change (base). Lower case letters from Tukey's HSD test indicate groups that are significantly different from each other. The unshaded cases on the left-hand side of the plot demonstrate changes under modelled present climate, and the shaded cases on the right-hand side of the plot demonstrate vegetation and soil changes under modelled future climate.



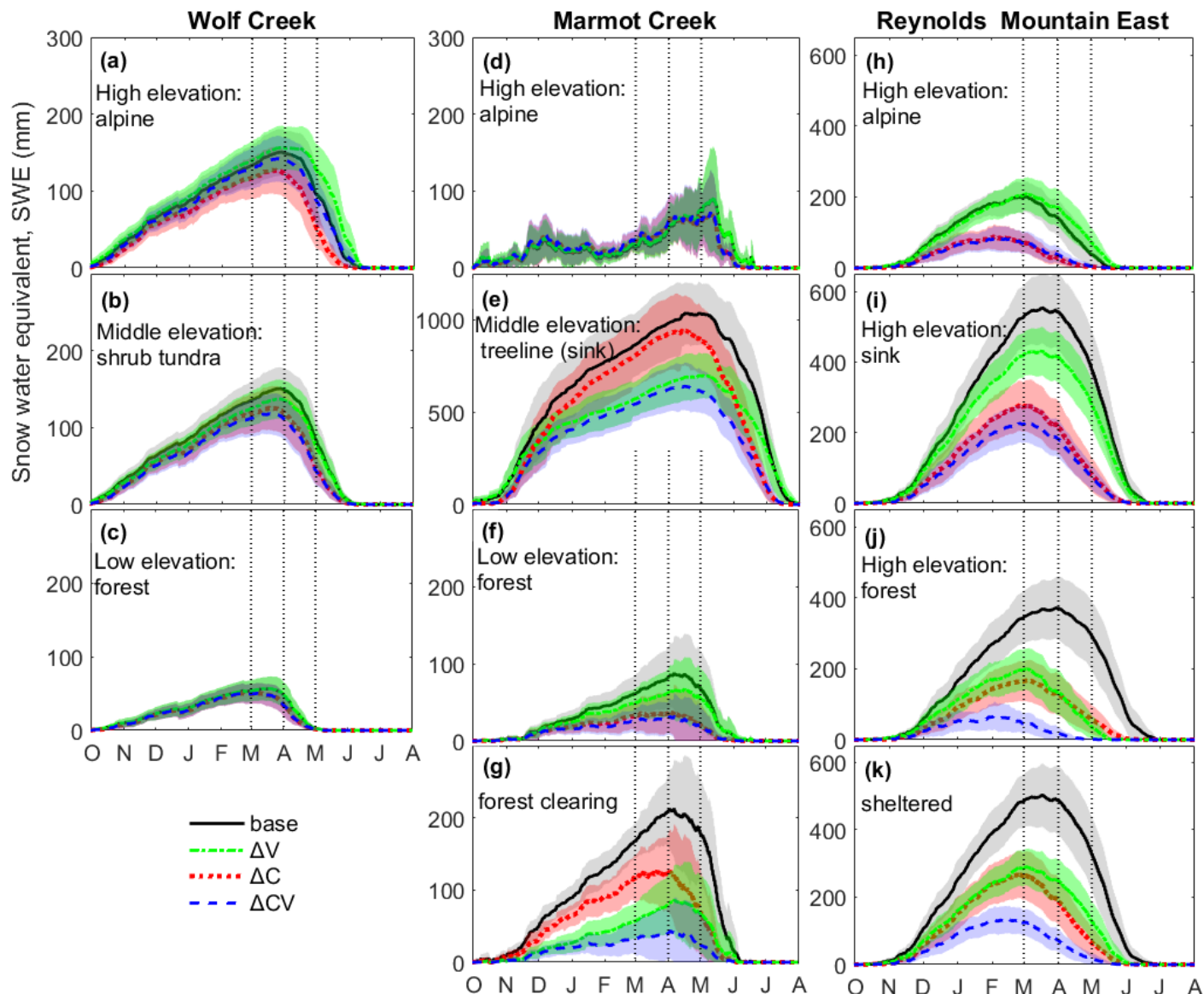
**Figure 5.** Differences in peak snow water equivalent (SWE) and annual runoff volume under seven combinations of changes in climate, vegetation, and soil in the Reynolds Mountain relative to present climate, present vegetation, and present soil with no change (base). Lower case letters from Tukey's HSD test indicate groups that are significantly different from each other. The unshaded cases on the left-hand side of the plot demonstrate changes under modelled present climate, and the shaded cases on the right-hand side of the plot demonstrate vegetation and soil changes under modelled future climate.

Basin-scale snow regime characteristics including peak SWE, length of the snow season, snow initiation date, mean annual peak SWE, and timing of snow-free date were simulated for current and future climate, vegetation, and soils in the three basins. Under the current climate, soil changes did not affect snow regime characteristics, and vegetation changes only decreased peak SWE in Marmot Creek (Table 3). Despite the decrease in peak SWE at the basin scale in Marmot Creek and for certain biomes in all basins, the timing of the basin-scale snow season was found to be insensitive to vegetation and soil changes under present climate in all basins (Table 3). Soil modules do not affect snow calculations in the CRHM models, and so soil changes do not affect snow regimes (Table 3 columns 2&3 and 4&5). The basin-scale peak SWE is affected by both climate and vegetation changes, and the changes are statistically significant based on the Mann–Whitney U-test ( $p$ -values  $\leq 0.05$ ).

The difference between times series and their spread of the present and future peak SWE modelled using driving meteorology from eleven regional climate models ( $11 \times n$  values) for  $n = 18$  years for Wolf Creek, 9 years for Marmot Creek, and 25 years for Reynolds Mountain are shown in Figure 6 and Table 4. Peak SWE decreases from 133 mm under the current climate to 118 mm (11% decrease) under climate change and to 107 mm (20%) when vegetation change is considered in combination with climate change in Wolf Creek. In Marmot Creek, peak SWE declines from the current climate value of 183 mm to 141 mm (23% decrease) under climate change and to 106 mm (42% decrease) under combined climate and vegetation change. An increase in precipitation under climate change in the north and a large vegetation change in Marmot Creek and its effect on accumulated snow lead to similar future peak snowpacks in Marmot Creek and Wolf Creek. The peak SWE in Reynolds Mountain decreases from 368 mm in the current climate to 196 mm (47% decrease) under climate change and to 168 mm (54% decrease) under combined climate and vegetation change. Considering only vegetation changes under the current climate, the peak SWE decreases more in Marmot Creek (26%) than in Wolf Creek and Reynolds Mountain (11%). Therefore, under the combined climate and vegetation change studied in this research, the maximum accumulated SWE is the most stable in Wolf Creek and most sensitive in Reynolds Mountain.

The significant responses to vegetation change ( $\Delta V$  in Figures 3-5) shows that vegetation change in all three basins has an important effect on snow and runoff regimes, except for the snow regimes in the alpine and forest biomes in Marmot Creek. Figure 6 shows the snowpack regimes in various current biomes and elevations for the three basins under current, changed climate  $\Delta C$ , changed vegetation  $\Delta V$ , and both changed climate and vegetation  $\Delta CV$  cases with shading to reflect interannual variability. The simulated snowpack regimes for  $\Delta C$ ,  $\Delta V$ , and  $\Delta CV$  are significantly ( $p$ -value  $\leq 0.05$ ) different from the base case in each biome shown in Figure 6 (Kolmogorov-Smirnov test); however there are important variations in how they differ. With  $\Delta V$ , SWE in Wolf Creek develops a greater peak and ablates more slowly, and the snowcover season becomes longer (Fig. 6a). This is mostly due to shrub expansion into higher elevations under  $\Delta V$ , which reduces blowing snow transport and subsequent sublimation of blowing snow and also slows snowmelt rates (Pomeroy et al., 2006). Changes in the rate of snowmelt can be assessed by comparison of the slope of the curve during the ablation period in Figure 6. There is no change in the slope between the base case and  $\Delta CV$  in alpine and forested biomes of Wolf Creek (Figure 6a-c) or in the alpine biomes of Marmot Creek (Figure 6d); however, these slopes decrease under  $\Delta CV$  at the middle elevations in Wolf Creek, the lower elevations in Marmot Creek, and at all elevations in Reynolds Mountain (Figures 6e-k), indicating a slower melt rate. Under  $\Delta CV$ , the effect of climate change on the alpine snowpack is moderated by the impact of the shrub tundra expansion into high elevation alpine tundra. However, at middle elevations, shrubs are expected to be replaced by forest; therefore, under  $\Delta CV$ , peak snowpack decreases from 156 mm to 127 mm (19 % decrease,

Fig. 6b). Vegetation change is expected to be negligible at low elevations in Wolf Creek, therefore, the snowpack is only disturbed by climate change impacts in these simulations (Fig. 6c).



305 **Figure 6.** Simulated snowpack accumulation and ablation under current climate and vegetation (**base scenario**) and changes due to climate and vegetation changes in different elevation levels and current biomes in Wolf Creek Research Basin, Marmot Creek Research Basin, and Reynolds Mountain. Reynolds Mountain has only one elevation band but multiple blowing snow regimes. The 95% confidence intervals shown by the shaded areas indicate the interannual variability. Three vertical lines denote the first days of March, April, and May.

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In Marmot Creek, anticipated advance of trees into alpine tundra causes a small increase in the simulated peak SWE and slower ablation rates at high elevations under the  $\Delta V$  scenario (Fig. 6d). In contrast to greater snowpacks with upward movement of the



315 treeline ( $\Delta V$ ), climate change alone ( $\Delta C$ ) slightly decreases peak SWE in the alpine. The treeline acts as an important sink for blowing snow transport and accumulates deep snowdrifts, so the effect of treeline movement out of upper middle elevations ( $\Delta V$ ) on reducing snowpacks is even greater than that of climate change ( $\Delta C$ ) (Fig. 6e). This is due to the suppression of snow redistribution to the former treeline with afforestation and subsequent sublimation of intercepted snow in newly forested needleleaf canopies, which is enhanced by climate change ( $\Delta CV$ ). At low elevations, snow accumulation decreases from 87 mm to 39 mm (48 mm) under combined climate change and conversion of forest to shrub and grass (Fig. 6f). Forest clearings currently store deep snowpacks; however, with regrowth of harvested forest, the peak snow will decrease as intercepted snow sublimation increases (Fig. 6g). Climate change has less impact than forest regrowth in these harvested clearings. In Marmot Creek, the impact of vegetation change on peak snowpack timing offsets the impact of climate change. The date of the peak SWE is delayed with only  $\Delta V$  and advanced with only  $\Delta C$  (Table 3).

325 In Reynolds Mountain, all blowing snow regimes except for the depressions and valley bottom (Fig. 6i) will receive a more uniform SWE under  $\Delta V$  as the forest canopy disappears. Despite the small impact of vegetation change in the alpine biome covered with grass and short mountain sages, the impact of  $\Delta C$  on the snowpack in this biome is large (Fig. 6h). The forest biome in Reynolds Mountain is most sensitive to  $\Delta CV$ , based on a large decrease in the peak snowpack (Fig. 6j). The interannual variability of SWE, which is expressed as 95% confidence intervals in Fig. 6, becomes smaller in all of the biomes within the three basins under climate perturbation because the snowpack becomes shallower under  $\Delta CV$  and variability of the shallow snowpack becomes smaller. This can occur despite an increased variability of precipitation under the future climate conditions. The interannual variability of SWE does not change in the alpine biome under  $\Delta V$ .

330 Snow regimes are the most resilient to  $\Delta CV$  at high elevations in Wolf Creek and Marmot Creek and low elevations in Wolf Creek, with less than 10% decrease in peak SWE. In contrast, snow regimes in the forest clearings in Marmot Creek and in the forest and sheltered sites in Reynolds Mountain are very sensitive to  $\Delta CV$ , with 80% and 68% decreases, respectively due to the role of canopy changes enhancing climate change impacts in reducing SWE. Under  $\Delta V$ , peak SWE drops from 87 mm to 46 mm (47% decrease) at low elevations in Marmot Creek with the conversion of forest into grassland. Impacts of  $\Delta C$  on snow regimes can be enhanced or dampened by the impact of  $\Delta V$ . Shrub tundra expansion into the higher elevations in Wolf Creek can substantially dampen the impact of climate change on snowpack because it suppresses blowing snow transport and sublimation. However, forest expansion above current treelines or into forest clearings enhances  $\Delta C$  impacts on the snowpack by introducing sublimation of intercepted snow. Therefore, the impact of shrubification or afforestation on the snowpack can be as important as the impact of climate change.

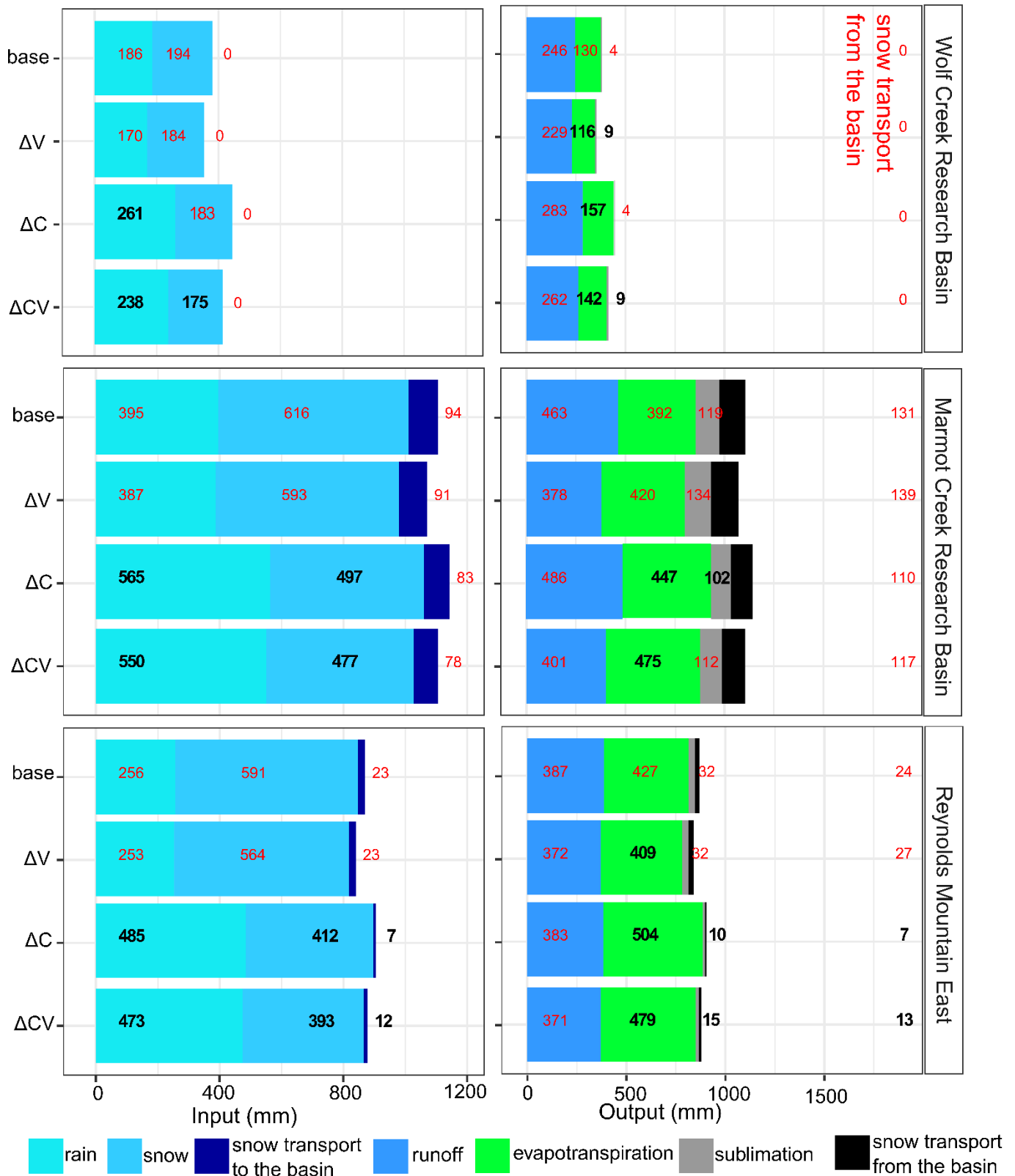
### 3.3 Precipitation Phase

345 With warmer air temperatures and increased precipitation, snowfall events become less frequent as the precipitation phase shifts from snowfall to rainfall (Figure 7). For the three basins (Figure 7), and their biomes (Figure 8), the portion of total precipitation that is rainfall increases in all of the basins under climate changes (vegetation change does not affect precipitation phase). Furthermore, annual rainfall rises to 238 mm out of 413 mm annual precipitation (rainfall ratio = 0.58) in Wolf Creek, 550 mm out of 1027 mm (rainfall ratio = 0.54) in Marmot Creek, and 473 mm out of 866 mm (rainfall ratio = 0.55) in Reynolds Mountain. For

all of the basins, the currently snowfall-dominated elevations, ranging between 650 m and 2500 m, are expected to become more rainfall-dominated under climate change.

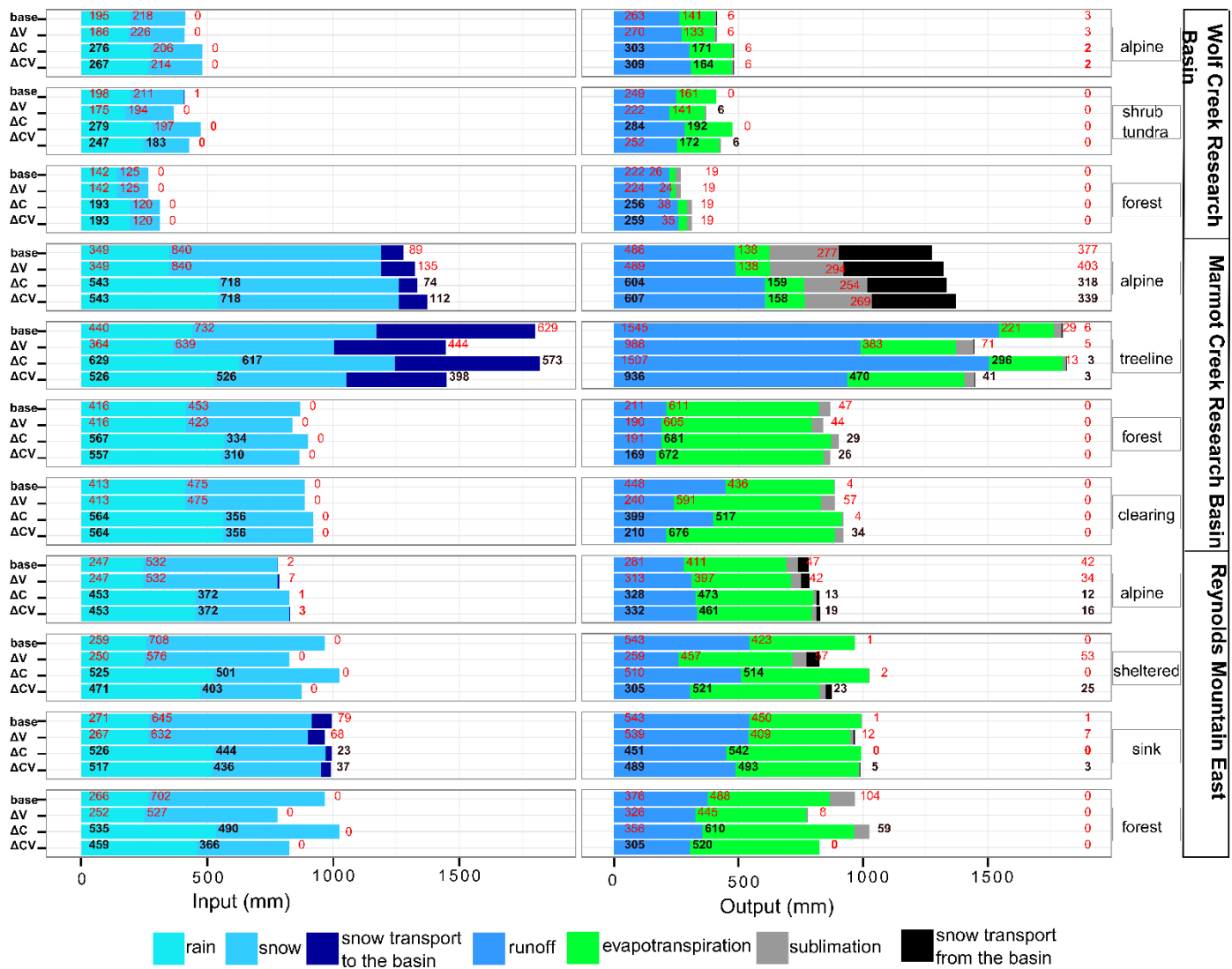
### 350 **3.4 Snow Transport and Redistribution**

355 The modelled snow redistribution due to blowing snow transport in and out of the basin and transport between biomes within a basin is an important component of the water budget that has been assessed in this study (Fig. 7 and 8). Under  $\Delta CV$ , the annual average blowing snow transport remains unchanged in Wolf Creek, while it declines 14 mm (from 131 mm to 117 mm) in Marmot Creek and 11 mm (from 24 mm to 13 mm) in Reynolds Mountain (Fig. 7). Snow transport at high elevations in Marmot Creek declines 11 mm under  $\Delta C$  and increases 23 mm due to shorter fetches as the treeline moves upslope with concomitant vegetation change ( $\Delta CV$ ). Therefore, the impact of climate change in reducing snow redistribution from the alpine biome in Marmot Creek is almost completely offset by vegetation change. At lower elevations where the treeline current exists, snow transport decreases 56 mm under  $\Delta C$ , likely due to higher threshold wind speeds for transport and a shorter snow season. Snow transport in the valley bottom and blowing snow sink regime in Reynolds Mountain, presently covered with a willow forest, also decreases substantially 360 from 79 mm to 37 mm (42 mm decrease,  $p$ -value  $\leq 0.05$ ) under climate change and deforestation ( $\Delta CV$ ).



**Figure 7.** Mean modelled water fluxes, in three states of liquid, vapor, and snow, under current climate and current vegetation (**base**), future climate and current vegetation ( $\Delta C$ ), (c) current climate and future vegetation ( $\Delta V$ ), and future climate and future vegetation ( $\Delta CV$ ) in Wolf Creek Research Basin, Marmot Creek Research Basin, and Reynolds Mountain. Statistically significant

differences in the climatological mean of the simulated variables with  $p$ -values less than 0.05 are represented by bold and black values.



370 **Figure 8.** Mean modelled water fluxes, in three states of liquid, vapor, and snow, on an elevation/vegetation basis under current climate and current vegetation (**base**), **current climate and future vegetation ( $\Delta V$ )**, **future climate and current vegetation ( $\Delta C$ )**, and **future climate and future vegetation ( $\Delta VC$ )** in Wolf Creek Research Basin, Marmot Creek Research Basin, and Reynolds Mountain. **Statistically significant differences** in the climatological mean of the simulated variables with  $p$ -values less than 0.05 are represented by bold and black values.

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### 3.5 Sublimation

The annual sublimation from all sources, including snow intercepted on the canopy, snow surface, and blowing snow was examined under climate and vegetation **changes and is shown in Figs. 7 and 8**. Sublimation from snow intercepted on the canopy in Wolf

380 Creek dominates the annual sublimation, which is expected to increase in this basin as the treeline moves upward to higher elevations. In Marmot Creek, annual sublimation increases 15 mm (Fig. 7, 119 to 134 mm) under  $\Delta V$  but decreases 7 mm under  $\Delta VC$  (Fig. 7, 119 to 112 mm). The impact of vegetation on sublimation rates in Reynolds Mountain is negligible, whilst climate change decreases sublimation from 31 mm to 10 mm. Vegetation change enhances sublimation with varying degrees in the different biomes of the three basins. Sublimation is suppressed by increasing shrub tundra in higher elevations. However,  $\Delta V$  causes sublimation to increase moderately in Marmot Creek and Wolf Creek basins due to enhanced sublimation of intercepted snow.  
385 Vegetation change does not affect sublimation in Reynolds Mountain.

### 3.6 Evapotranspiration (ET)

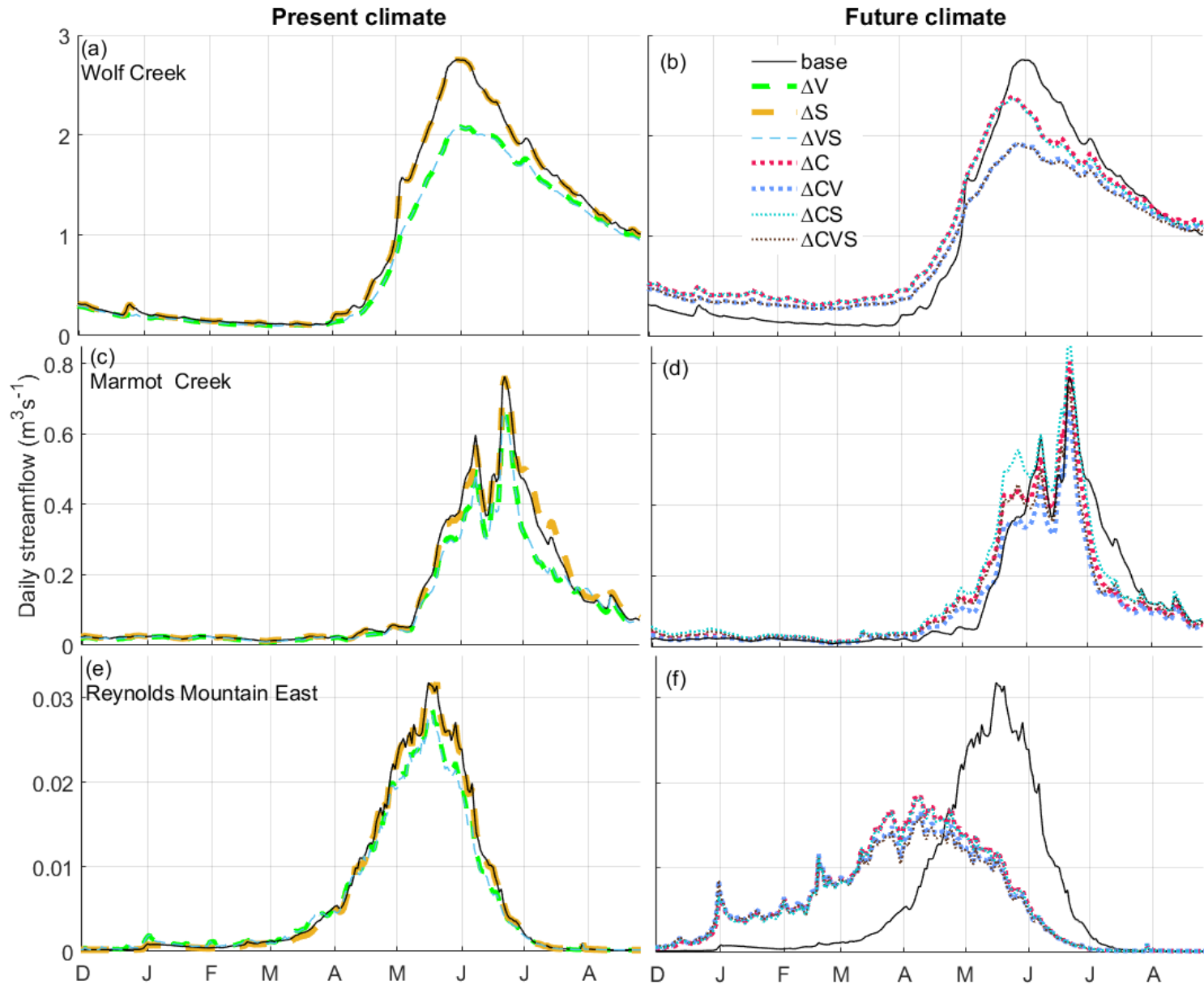
$\Delta V$  also alters the annual evapotranspiration (ET). The simulations show that, under  $\Delta V$ , annual ET increases 28 mm (from 392 to 420 mm, Figure 7) as a result of afforestation of the clearings and upward movement of the treeline in Marmot Creek. In contrast, ET decreases 14 mm in Wolf Creek (from 130 to 116 mm, Figure 7) and 18 mm in Reynolds Mountain (from 427 to 409 mm, Figure 7). Increases in ET due to  $\Delta C$  can be partially offset by concomitant vegetation change in Wolf Creek and Reynolds Mountain. ET increases the most in Marmot Creek, from 392 mm to 475 mm (83 mm,  $p$ -value < 0.05), and the least in Wolf Creek, from 130 mm to 142 mm (12 mm), under both vegetation and climate changes. Under  $\Delta VC$ , ET changes significantly in different elevation bands (Figure 8). The increase in ET due to  $\Delta CV$  varies with elevation within each basin and reaches 23 mm at high elevations and 9 mm at low elevations in Wolf Creek, 61 mm at low elevations and 249 mm in the treeline elevations in Marmot Creek, and 32 mm in the forest and 98 mm in the sheltered site in Reynolds Mountain (Fig. 8). This also shows the high variability of the annual ET amongst these three basins.  
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### 3.7 Runoff characteristics

$\Delta V$  decreases annual runoff volume in Wolf Creek, which counteracts with the increasing effect of climate change on annual runoff volume (Table 5, Fig. 3d). Changes in soil and vegetation decrease annual runoff volume in Marmot Creek (Table 5, Fig. 4e). With  $\Delta VC$ , annual runoff volume decreases in Marmot Creek, while under combined climate – soil changes it increases (Table 5, Fig. 4e). This shows that a combination of all, vegetation, and soil changes have respectively the largest to lowest effect, and climate change has no effect on annual runoff volume in Marmot Creek. In Reynolds Mountain, change in annual runoff is evidenced only under current climate and future vegetation (Table 5, Fig. 5e).  
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The average annual hydrographs for the present and future climates simulations under vegetation and soil changes are shown in Figure 9. With  $\Delta V$ , high flows are lower in all three basins, particularly in Wolf Creek (Fig. 9a).  $\Delta C$  shifts high flows to occur earlier in Wolf Creek (Fig. 9b), and leads to no changes in Marmot Creek (Fig. 9d) and much earlier in Reynolds Mountain (Fig. 9f). Climate ( $\Delta C$ ) and soil changes ( $\Delta S$ ) do not cause significant changes in annual runoff volumes in Marmot Creek and Reynolds Mountain, while in Wolf Creek climate change ( $\Delta C$ ) increases and soil change ( $\Delta S$ ) decreases the annual runoff volume (246 to 210mm, Table 4, Fig. 3d). The combined effect of climate – vegetation change ( $\Delta CV$ ) in these simulations advanced the snow-free date by 14 days in Wolf Creek, 11 days in Marmot Creek, and 46 days in Reynolds Mountain and decreased the length of the snowcover season by 9, 37, and 40 days in Wolf Creek, Marmot Creek, and Reynolds Mountain, respectively (Table 4).  $\Delta CV$  delayed the snow accumulation initiation date by 15 days in Marmot Creek and 14 days in Reynolds Mountain. The beginning of  
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the melt season under  $\Delta CV$ , measured from the timing of peak SWE, advanced 22 days (April 4 to March 13) in Wolf Creek, and 34 days (March 10 to February 4) in Reynolds Mountain (Table 4). The shift in the timing of the melt season was reflected in the runoff timing (Fig. 9b & f, Table 4).



**Figure 9.** Annual average hydrographs under present climate, present vegetation, and present soil (base), present climate, future vegetation, present soil ( $\Delta V$ ), present climate, present vegetation, future soil ( $\Delta S$ ), present climate, future vegetation, future soil ( $\Delta VS$ ), future climate, present vegetation, present soil ( $\Delta C$ ), future climate, future vegetation, present soil ( $\Delta CV$ ), future climate, present vegetation, future soil ( $\Delta CS$ ), and future climate, future vegetation, future soil ( $\Delta CVS$ ) in the three basins.

#### 4 Discussion`

425 The interaction of vegetation, soil, and climate changes can either **result in** large changes in snow and runoff regimes or offset  
effect **of each other**. For instance, an insignificant increase in peak SWE in the alpine biome **in Wolf Creek under  $\Delta V$**  can become  
important with concomitant climate change in that it can offset the climate change effect under  $\Delta CV$  (Fig. 3a).  $\Delta V$  decreases  
annual runoff in Wolf Creek while  $\Delta C$  counteracts the effect of vegetation change and increases the annual runoff with  $\Delta CV$  (Fig.  
3d). The individual effects of soil ( $\Delta S$ ) and climate change ( $\Delta C$ ) on annual runoff **in Marmot Creek are statistically insignificant,**  
430 **but when they are combined ( $\Delta CS$ ), the effect of the combination is enhanced, leading to a statistically significant increase in**  
**annual runoff volume (Fig. 4e). Therefore, the increase in annual runoff volume by climate change ( $\Delta C$ ) is offset by vegetation**  
**change effect ( $\Delta CV$ ) in Wolf Creek, and it is enhanced by soil change effect ( $\Delta S$ ) in Marmot Creek,** while the effect of climate  
change ( $\Delta C$ ) on annual runoff in Reynolds Mountain is not significant, and the vegetation change ( $\Delta V$ ) is the main driver of the  
runoff changes in this basin. A decreasing effect of vegetation change on annual runoff in Marmot Creek is offset by a combined  
435 soil and climate change ( $\Delta CVS$  and base are in the same group in Fig. 4e). This suggests that not only climate change but also  
vegetation and soil changes affect hydrological processes in cold regions, and small changes can trigger significant hydrological  
changes if changes concur. Therefore, consideration of all vegetation, soil, and climate changes in impact studies is necessary  
(Pielke, 2005), especially in the basins with near-freezing winter air temperatures such as Reynolds Mountain, where vegetation –  
atmosphere interactions are complex and nonlinear and can dampen or amplify climate change (Bonan, 2008).

440 **Similar to findings of Musselman et al. (2017) in the mountains of the western USA and south-western Canada, future snowmelt**  
**rates with combined climate and vegetation change were found to be slower than the present-climate rates in Reynolds Mountain**  
**and lower elevations in Marmot Creek (Fig. 6f-k). In contrast, snowmelt rates under the combined effect of climate change and**  
**anticipated shrub expansion into alpine tundra in Wolf Creek (Fig. 6a) and upslope forest expansion in Marmot Creek (Fig. 6d)**  
**remained similar to the present-climate rates. Shrubs expansion into higher elevations prolongs the snow season and increases peak**  
445 **SWEs, counteracting climate change impact on snowmelt. Therefore, relative to the base case no change in the future snowmelt**  
**was found under vegetation and climate changes in cold and high elevation environments. Though these snowmelt rates did not**  
**decelerate under climate change as Musselman et al. (2017) found in warmer environments, neither did they accelerate as found**  
**by Krogh and Pomeroy (2019) in a colder Arctic basin located 1000 km north of Wolf Creek.**

Under combined climate and vegetation changes in Wolf Creek, precipitation and rainfall ratio increase (Fig. 8), peak SWE declines  
450 (Table 4), ET and sublimation increases (Fig. 8), and snow season period shortens (Table 4), which result in no change in annual  
total runoff (Fig. 3d). This implies that the climate change effect on increasing annual runoff in Wolf Creek is offset by the  
vegetation change effect on decreasing annual runoff and increased precipitation effect is offset by increased sublimation and ET  
in Wolf Creek (Rasouli et al., 2019a). Unlike Wolf Creek, annual runoff volume declines under combined climate and vegetation  
changes ( $\Delta CV$  case) in Marmot Creek (Fig. 4e), which is due to significant decreases in sublimation and snow transport and  
455 increase in ET (Fig. 8 and 9). The response of simulated annual total runoff to climate and vegetation changes varies. Annual  
runoff increases from Reynolds Mountain in the south to Wolf Creek in the north under only climate and both climate – soil  
changes, consistent with findings of Nijssen et al. (2001). Annual runoff increases with climate change in Wolf Creek (Fig. 3d)  
and Marmot Creek (Fig. 4e), and decreases with only vegetation or vegetation – soil changes in all three basins, consistent with  
Bosch and Hewlett (1982), and with only soil changes in Wolf Creek (Fig. 3e). Despite the snow regime in Reynolds Mountain,  
460 which is sensitive to both climate and vegetation changes, only vegetation change affects annual total runoff (Fig. 5e). Vegetation

change moderates the impact of climate change on ET to some extent by decreasing ET in Wolf Creek and Reynolds Mountain (Figure 7 & 8). Under a combined climate and vegetation change, ET increases in the three basins across the North American Cordillera (Fig. 7). The response of the peak SWE to climate and vegetation changes leads to a complex response of the annual runoff when soil and precipitation phase changes are also considered. Changes in runoff characteristics become statistically significant when combined climate – vegetation – soil changes ( $\Delta CVS$ ) occur in Reynolds Mountain (Fig. 5e), climate – soil changes ( $\Delta CS$ ) occur in Marmot Creek (Fig. 4e), and soil – vegetation changes ( $\Delta VS$ ) occur in Wolf Creek (Fig. 3e).

A deep snowpack is deposited at middle elevations in Marmot Creek because of the strong winds, which scour blowing snow from the higher elevations to the treeline (MacDonald et al., 2010). Under the simulations presented in this paper and ongoing vegetation growth, alpine vegetation and shrubs in the treeline will eventually convert to forest, which can change the snow regime from a present-day blowing snow sink to a future forest with intercepted snow on the canopy. A simulated snow regime change at middle elevations in Marmot Creek leads to a substantial decrease in the maximum accumulated snowpack (Fig. 4c). This is because of the shift in the forest role from slowing snowmelt by shading the snow and sheltering the snow from wind to accelerating midwinter snowmelt by removal of the forest canopy (Lundquist et al., 2013). The peak SWE at low elevations also declines under future deforestation and climate change in Marmot Creek (Fig. 4b and Fig. 7f). This is because sublimation from blowing snow within the deforested portion of the lower elevations becomes more important than sublimation from intercepted snow on the canopy before deforestation. A higher sublimation rate on the slopes with no vegetation cover was also reported by Liston et al. (2002). Forest regrowth also delays snow ablation because of the lower net radiation under the canopy relative to clearings with no canopy (Gelfan et al., 2004; Ellis et al., 2010). The impact of afforestation on snowpack in the forest clearings is stronger than that of climate change. Therefore, an enhanced snowpack decline is expected in forest clearings under climate and vegetation changes (Fig. 4c and Fig. 7g).

Sublimation losses do not only vary from one basin to another but vary among the different elevation bands within each basin. For instance, at high elevations in Wolf Creek, shrub tundra expansion enhances the sublimation by increasing the snowpack. In contrast, both snowpack and sublimation decrease under climate change. This shows that, in the alpine biome of Wolf Creek, the impact of vegetation change on sublimation can be as important as the impact of climate change and a combined climate and change leads to an unchanged sublimation rate. At middle elevations in Wolf Creek covered currently by shrub tundra, a treeline shift into the shrub tundra biome increases sublimation, while the opposite is true under climate change when snowpack and sublimation both decrease. No changes are expected in the sublimation at low elevations in Wolf Creek. Similar to Wolf Creek, the impact of a combined climate and vegetation change on sublimation in Marmot Creek varies with elevation. It causes an 8 mm decrease at high elevations as a result of the upward movement of the treeline, a 12 mm increase in the treeline blowing snow sink regime as shrubs turn to forest, and a 21 mm decrease at low elevations as forest becomes uncovered and snowpack becomes shallower with warming. Different mechanisms are responsible for these changes; annual sublimation decreases in the alpine biome with the upward movement of the treeline as sublimation from blowing snow drops with upslope forest expansion. At middle elevations, bushes are replaced by trees and sublimation from intercepted snow on their canopy slightly increases. The combination of topographic gradients and types of vegetation plays an important role in snow redistribution and blowing snow sublimation. The highest wind-driven redistribution of snow and the highest sublimation occurs on leeward slopes, where there is little or no vegetation cover (Liston et al., 2002). At low elevations in Marmot Creek, sublimation from intercepted snow on the canopy decreases as deforestation occurs. This also occurs in the deforested zone in Reynolds Mountain in which sublimation



significantly decreases from 104 mm to 8 mm as a result of decreased available snow combined with deforestation under climate change.

500 Shrub tundra expansion to higher elevations (Myers-Smith and Hik, 2018), community height increase (Bjorkman et al., 2018), and increase of tree growth rates (Innes, 1991) have shifted the windblown snow drifts into higher elevations (Fig. 4a; Fig. 6a), which has offset the climate warming effect on decreasing peak SWE in the alpine biome in Wolf Creek (Fig. 3a). A 20–60 % increase in tundra height is expected by the end of the century (Bjorkman et al., 2018), which may change snow redistribution and soil moisture availability in the higher latitudes. Despite a long snowcover period in higher elevations with shrub tundra expansion, 505 which may slow the growth rate, snow insulates and warms the soil and increases the productivity chance, leading to more expansion of the warmth-demanding vegetation types such as shrub tundra (Lamprecht et al., 2018). The balance of these feedbacks in the future may depend on the changes in air temperature, snow redistribution, and soil moisture and their interactions (Lawrence and Swenson, 2011).

510 In different biomes in each basin, the timing of the basin-scale snowcover season was found to be insensitive to vegetation and soil changes under present climate (Table 3). This result differs from other studies that have found snowcover to be sensitive to vegetation on the Prairies (Pomeroy and Gray, 1994), in the Alps (Keller et al., 2005) and in shrub tundra (Pomeroy et al., 2006). Biomes that are insensitive in our study are located at cold high elevations, where the snowpack is more resilient (Rasouli et al., 2019a)

515 The simulation results presented here consider one future climate scenario (A2 SRES) and generalized vegetation and soil changes that can be expected. The simulations compare ‘snapshots’ in time comparing eight steady state conditions based upon a monthly climate perturbation based upon RCM projections that has preserved the past history of observed weather in these three basins. Future weather may not necessarily resemble what has been observed in the past. While steady state conditions are useful for examining the complex interactions between the effects of changes in climate, vegetation, and soil, as presented here, transient models that could capture the sequence of asynchronous changes in climate, vegetation, and soil, and potential feedback are needed to fully understand the ongoing changes in mountain watersheds. 520

Shifts in the timing of snow accumulation and snowmelt seasons have important consequences and can change the timing, rate, and amounts of runoff in snow-dominated mountain basins (Callaghan et al., 2011). The simulation results presented here demonstrate that the interactions of changes in climate, vegetation, and soils are complex. Studies that consider the future impacts of climate change should not exclude consideration of the role of future vegetation.

525

## 5 Conclusions

Snow and runoff in three headwater mountain basins along the North American Cordillera are vulnerable to changes in climate, vegetation, and soil. A physically based semi-distributed hydrological model driven with monthly perturbed climate based on observations and modelled changes in monthly climatology. Changes in monthly climatology were obtained from eleven regional climate models. Climate changes, vegetation and soil changes each affect cold regions hydrological mechanisms. The effects of 530

535 vegetation changes can be as large as those of climate change alone and decrease peak SWE at middle elevations, and sublimation amounts. Shrub tundra expansion to higher elevations in Wolf Creek shifted the windblown snow drifts into higher elevations, which offset the climate warming effect on decreasing peak SWE in the alpine biome. At high elevations, the impact of climate change on peak SWE, snow transport in Reynolds Mountain, ET, and annual total runoff is partially offset by the impact of vegetation change.

540 Simulations suggest that under both climate change and soil changes annual total runoff is expected to gradually increase from Reynolds Mountain in the south to Wolf Creek in the north of the Cordillera. With both vegetation and soil changes, annual runoff will decrease. Simulations suggest that with all three changes (climate, vegetation, and soil) annual runoff will decrease in Reynolds Mountain, and remain unchanged in Marmot Creek and in Wolf Creek. The annual runoff volume decrease under soil change is larger than the annual runoff volume increases under climate change in Wolf Creek. Furthermore, the soil change has a more important role than the vegetation change in decreasing runoff volume in Wolf Creek. To some extent, the interaction of soil – climate changes moderates the counteracting decreasing effect of soil change and increasing effect of climate change on annual runoff volume. Interaction of soil – climate changes has also a more important role in increasing annual runoff volume than the effect of only climate, only soil change, or interaction of all three soil – vegetation – climate changes in Marmot Creek. Further investigation in other mountainous regions, especially in regions with winter temperatures near freezing is needed to better assess the impact of combined climate, vegetation, and soil changes. Mountain water resources systems that are vulnerable to warming and land cover changes can be identified using the modelling strategy present here. Future vegetation and soil changes need to be considered, in addition to a changing climate, to reduce the uncertainties about the changing mountain hydrology.

550 **Data availability.** Long-term datasets and descriptions of the variables for each basin were published by Reba et al. (2011), Fang et al. (2019), and Rasouli et al. (2019b).

**Author contribution.** All three coauthors contributed to the research design and the writing of the manuscript. KR developed the models for Wolf Creek and Marmot Creek. JWP managed and supervised the research. PHW helped in statistical analysis.

**Competing interests.** The authors declare that they have no conflict of interest.

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## References

- 565 Alberta Natural Regions Committee: in *Natural Regions and Subregions of Alberta*, Compiled by D. J. Downing and W. W. Petapiece, Government of Alberta Publication Number T/852, pp. 254, 2006.
- Abdi, H., and Williams, L. J.: Tukey's honestly significant difference (HSD) test, In *Encyclopedia of Research Design*, (Ed.) Neil Salkind, Thousand Oaks, CA: Sage, pp.1-5, 2010.
- Bales, R. C., Hopmans, J. W., O'Geen, A. T., Meadows, M., Hartsough, P. C., Kirchner, P., Hunsaker, C. T., and Beaudette, D.: Soil moisture response to snowmelt and rainfall in a Sierra Nevada mixed-conifer forest, *Vadose Zone J.*, 10 (3), 786–799, 2011.
- 570 Beniston, M.: Climatic change in mountain regions: a review of possible impacts, in *Climate variability and change in high elevation regions: past, present & future*, 5–31, Springer, 2003.
- Bennett, K. E., Werner, A. T., and Schnorbus, M.: Uncertainties in hydrologic and climate change impact analyses in headwater basins of British Columbia, *J. Climate*, 25 (17), 5711–5730, 2012.
- 575 Billings, W. D., and Bliss, L.: An alpine snowbank environment and its effects on vegetation, plant development, and productivity, *Ecology*, 40 (3), 388–397, 1959.
- Bjorkman, A.D., Myers-Smith, I. H., Elmendorf, S. C., Normand, S., Rüger, N., Beck, P. S., Blach-Overgaard, A., Blok, D., Cornelissen, J. H. C., Forbes, B. C. and Georges, D., et al.: Plant functional trait change across a warming tundra biome, *Nature*, 562(7725), pp. 57, 2018.
- 580 Bonan, G. B.: Forests and climate change: forcings, feedbacks, and the climate benefits of forests, *Science*, 320(5882), 1444–1449, 2008.
- Bosch, J. M. and Hewlett, J.: A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration, *J. Hydrol.*, 55 (1), 3–23, 1982.
- Brown, A. E., Zhang, L., McMahon, T. A., Western, A. W., and Vertessy, R. A.: A review of paired catchment studies for determining changes in water yield resulting from alterations in vegetation, *J. Hydrol.*, 310 (1), 28–61, 2005.
- 585 Callaghan, T. V., Johansson, M., Brown, R. D., Groisman, P. Y., Labba, N., Radionov, V., Bradley, R. S., Blangy, S., Bulygina, O. N., Christensen, T. R., Coleman, J. E., Essery, R. L. H., Forbes, B. C., Forchhammer, M. C., Golubev, V. N., Honrath, R. E., Juday, G. P., Mehcherskaya, A. V., Phoenix, G. K., Pomeroy, J., Rautio, A., Robinson, D. A., Schmidt, N. M., Serreze, M. C., Shevchenko, V. P., Shiklomanov, A. I., Shmakin, A. B., Sköld, P., Sturm, M., Woo, M.-K., and Wood, E. F.: Multiple effects of changes in Arctic snow cover, *Ambio*, 40, 32-45, 2011.
- 590 Crocker, R. L. and Major, J.: Soil development in relation to vegetation and surface age at Glacier Bay, Alaska, *J. Ecol.*, 427–448, 1955.
- Dale, V. H. and Franklin, J. F.: Potential effects of climate change on stand development in the Pacific Northwest, *Can. J. For. Res.*, 19 (12), 1581–1590, 1989.
- 595 DeBano, L. F.: The effect of fire on soil properties, General Technical Report, Tech. rep., United States Department of Agriculture, Forest Service INT-280, 151–156, 1991.

- DeFries, R. and Eshleman, K. N.: Land-use change and hydrologic processes: A major focus for the future, *Hydrol. Process.*, 18 (11), 2183–2186, 2004.
- 600 Ellis, C. R., Pomeroy, J. W., Brown, T., and MacDonald, J. P.: Simulation of snow accumulation and melt in needleleaf forest environments, *Hydrol. Earth Syst. Sci.*, 14, 925–940, <https://doi.org/10.5194/hess-14-925-2010>, 2010.
- Fang X., Pomeroy J. W., Ellis, C., MacDonald, M., DeBeer, C., and Brown, T.: Multi-variable evaluation of hydrological model predictions for a headwater basin in the Canadian Rocky Mountains, *Hydrol. Earth Syst. Sci.*, 17 (4), 1635–1659, 2013.
- Fang, X., Pomeroy, J. W., DeBeer, C. M., Harder, P. and Siemens, E.: Hydrometeorological data from Marmot Creek Research Basin, Canadian Rockies, *Earth Syst. Sci. Data*, 11(2), 455–471, 2019.
- 605 Flerchinger, G. N., Reba, M. L., and Marks, D.: Measurement of surface energy fluxes from two rangeland sites and comparison with a multilayer canopy model, *J. Hydrometeorol.*, 13 (3), 1038–1051, 2012.
- Fowler, H., Blenkinsop, S., and Tebaldi, C.: Linking climate change modelling to impacts studies: recent advances in downscaling techniques for hydrological modelling, *Int. J. Climatol.*, 27 (12), 1547–1578, 2007.
- Francis, S., Smith, S., and Janowicz, R.: Data integration and ecological zonation of Wolf Creek watershed, in *Wolf Creek Research Basin–Hydrology, Ecology, Environment–Proceedings of a workshop held in Whitehorse, Yukon*, edited by: Pomeroy, J. W. and Granger R. J., pp. 93–100, Citeseer, 1998.
- 610 Gelfan, A. N., Pomeroy, J. W., and Kuchment, L. S.: Modeling forest cover influences on snow accumulation, sublimation, and melt, *J. Hydrometeorol.*, 5(5), 785–803, 2004.
- Goodison, B., Louie, P., and Yang, D.: The WMO solid precipitation measurement intercomparison, *World Meteorological Organization-Publications-WMO TD*, pp. 65–70, 1998.
- 615 Gutmann, E., Barstad, I., Clark, M., Arnold, J., and Rasmussen, R.: The Intermediate Complexity Atmospheric Research Model (ICAR). *J. Hydrometeorol.*, 17(3), 957–973, 2016.
- Hallinger, M., Manthey, M., and Wilmking, M.: Establishing a missing link: warm summers and winter snow cover promote shrub expansion into alpine tundra in Scandinavia, *New Phytol.*, 186 (4), 890–899, 2010.
- 620 Halofsky, J. E., Peterson, D. L., and Prendeville, H. R.: Assessing vulnerabilities and adapting to climate change in northwestern US forests, *Climatic Change* 146, 89-102, 2018.
- Hansell, R., Chant, D., and Weintraub, J.: Changes in the northern limit of spruce at Dubawnt Lake, Northwest Territories, Arctic, 24 (3), 233–234, 1971.
- Hay, L. E., Wilby, R. L., and Leavesley, G. H.: A comparison of delta change and downscaled GCM scenarios for three mountainous basins in the United States, *JAWRA, J. Am. Water Resour. Assoc.*, 36 (2), 387–397, 2000.
- 625 Hijmans, R. J., Cameron, S. E., Parra, J. L., Jones, P. G., and Jarvis, A.: Very high resolution interpolated climate surfaces for global land areas, *Int. J. Climatol.*, 25(15), 1965–1978, 2005.
- Innes, J.: High-altitude and high-latitude tree growth in relation to past, present and future global climate change, *The Holocene*, 1 (2), 168–173, 1991.

- 630 Kay, A., Davies, H., Bell, V., and Jones, R.: Comparison of uncertainty sources for climate change impacts: flood frequency in England, *Clim. Chang.*, 92(1), 41–63, 2009.
- Kirby, C. and Ogilvie, R.: The forests of Marmot Creek watershed research basin, 47–1259, 1–37 pp., Canadian Forestry Service, Queen's Press, pp. 37, 1969.
- Keller, F., Goyette, S., and Beniston, M.: Sensitivity analysis of snow cover to climate change scenarios and their impact on plant habitats in alpine terrain, *Climatic Change*, 72, 299–319, 2005.
- 635 Köppen, W.: Das geographische System der Klimate, in: *Handbuch der klimatologie*, edited by: Köppen, W., and Geiger, R., Band 1, Teil C, Gebrüder Borntraeger Berlin, 44, 1936.
- Krogh, S. A. and Pomeroy, J. W.: Recent changes to the hydrological cycle of an Arctic basin at the tundra–taiga transition, *Hydrol. Earth Syst. Sci.*, 22(7), 3993–4014, 2018.
- 640 Krogh, S. A., and Pomeroy, J. W.: Impact of future climate and vegetation on the hydrology of an Arctic headwater basin at the tundra–taiga transition, *J. Hydrometeorol.*, 20(2), 197–215, 2019.
- Lamprecht, A., Semenchuk, P. R., Steinbauer, K., Winkler, M., and Pauli, H.: Climate change leads to accelerated transformation of high-elevation vegetation in the central Alps. *New Phytol.*, 220(2), 447–459, 2018.
- Lawrence, D. M. and Swenson, S. C.: Permafrost response to increasing Arctic shrub abundance depends on the relative influence of shrubs on local soil cooling versus large-scale climate warming, *Environ. Res. Lett.* 6, 045504, 2011.
- 645 Lewkowicz, A. G. and Ednie, M.: Probability mapping of mountain permafrost using the BTS method, Wolf Creek, Yukon Territory, Canada, *Permafrost Periglacial Process.*, 15 (1), 67–80, 2004.
- Link, T. E., Flerchinger, G. N., Unsworth, M., and Marks, D.: Simulation of water and energy fluxes in an old-growth seasonal temperate rain forest using the simultaneous heat and water (SHAW) model, *J. Hydrometeorol.*, 5 (3), 443–457, 2004.
- 650 Liston, G. E., Mcfadden, J. P., Sturm, M., and Pielke, R. A.: Modelled changes in arctic tundra snow, energy and moisture fluxes due to increased shrubs, *Glob. Chang. Biol.*, 8 (1), 17–32, 2002.
- Lundquist, J. D., Dickerson-Lange, S. E., Lutz, J. A., and Cristea, N. C.: Lower forest density enhances snow retention in regions with warmer winters: A global framework developed from plot-scale observations and modeling, *Water Resour. Res.*, 49 (10), 6356–6370, 2013.
- 655 MacDonald, M. K., Pomeroy, J. W., and Pietroniro, A.: Parameterizing redistribution and sublimation of blowing snow for hydrological models: tests in a mountainous subarctic catchment, *Hydrol. Process.*, 23 (18), 2570–2583, 2009.
- MacDonald, M. K., Pomeroy, J. W., and Pietroniro, A.: On the importance of sublimation to an alpine snow mass balance in the Canadian Rocky Mountains, *Hydrol. Earth Syst. Sci.*, 14(7),1401–1415, 2010.
- Macias-Fauria, M. and Johnson, E. A.: Large-scale climatic patterns and area affected by mountain pine beetle in British Columbia, Canada, *J. Geophys. Res.: Biogeosci.*, 114 (G1), doi:10.1029/2008JG000760, doi:10.1029/2008JG000760, 2009.
- 660 Mann, D. H., Scott Rupp, T., Olson, M. A., and Duffy, P. A.: Is Alaska's boreal forest now crossing a major ecological threshold?, *Arct., Antarc., Alp. Res.*, 44 (3), 319–331, 2012.

- Mann, H. B. and Whitney, D. R.: On a test of whether one of two random variables is stochastically larger than the other, *Ann. Math. Stat.*, 18 (1), 50–60, 1947.
- 665 Martin, A. C., Jeffers, E. S., Petrokofsky, G., Myers-Smith, I., and Macias-Fauria M.: Shrub growth and expansion in the Arctic tundra: an assessment of controlling factors using an evidence-based approach, *Environ. Res. Lett.*, 12(8), p.085007, 2017.
- Massey Jr., F. J.: The Kolmogorov-Smirnov test for goodness of fit, *J. Am. Stat. Assoc.*, 46 (253), 68–78, 1951.
- Mearns, L., Gutowski, W., Jones, R., Leung, L., McGinnis, S., Nunes, A., and Qian, Y.: The North American regional climate change assessment program dataset, National Center for Atmospheric Research Earth System Grid Data Portal, Boulder, CO, doi:10.5065/D6RN35ST, 2007.
- 670 **Musselman, K. N., Clark, M. P., Liu, C., Ikeda, K., and Rasmussen, R.: Slower snowmelt in a warmer world, *Nature Climate Change*, 7(3), p.214, 2017.**
- Myers-Smith, I. H. and Hik, D. S.: Climate warming as a driver of tundra shrubline advance, *J. Ecol.*, 106(2), 547–560, 2018.
- Neilson, R. P. and Marks, D.: A global perspective of regional vegetation and hydrologic sensitivities from climatic change, *J. Veg. Sci.*, 5 (5), 715–730, 1994.
- 675 Nijssen, B., O'donnell, G. M., Hamlet, A. F., and Lettenmaier, D. P.: Hydrologic sensitivity of global rivers to climate change, *Clim. Chang.*, 50 (1-2), 143–175, 2001.
- Osterkamp, T., Jorgenson, M., Schuur, E., Shur, Y., Kanevskiy, M., Vogel, J., and Tumskey, V.: Physical and ecological changes associated with warming permafrost and thermokarst in interior Alaska, *Permafrost Periglacial Process.*, 20 (3), 235–256, 2009.
- 680 Pielke, R. A.: Land use and climate change, *Science*, 310 (5754), 1625–1626, 2005.
- Pomeroy, J. W., and Gray, D. M.: Sensitivity of snow relocation and sublimation to climate and surface vegetation, *IAHS Publications-Series of Proceedings and Reports-Intern Assoc Hydrological Sciences*, 223, 213-226, 1994.**
- Pomeroy, J. W., Gray, D. M., Brown, T., Hedstrom, N., Quinton, W., Granger, R. J., and Carey, S.: The cold regions hydrological model: A platform for basing process representation and model structure on physical evidence, *Hydrol. Processes*, 21, 2650–2667, <https://doi.org/10.1002/hyp.6787>, 2007.**
- 685 Pomeroy, J. W., Hedstrom, N., and Parviainen, J.: The snow mass balance of Wolf Creek, Yukon: effects of snow sublimation and redistribution, *Wolf Creek Research Basin–Hydrology, Ecology, Environment–Proceedings of a workshop held in Whitehorse, Yukon*, edited by: Pomeroy, J. W. and Granger R. J., 15–30, 1999.
- 690 Pomeroy, J. W., Bewley, D., Essery, R., Hedstrom, N., Link, T., Granger, R., Sicart, J.-E., Ellis, C., and Janowicz, J.: Shrub tundra snowmelt, *Hydrol. Process.*, 20 (4), 923–941, 2006.
- Pomeroy, J., Toth, B., Granger, R., Hedstrom, N., and Essery, R.: Variation in surface energetics during snowmelt in a subarctic mountain catchment, *J. Hydrometeorol.*, 4 (4), 702–719, 2003.
- Pomeroy, J., Bewley, D., Essery, R., Hedstrom, N., Link, T., Granger, R., Sicart, J.-E., Ellis, C., and Janowicz, J.: Shrub tundra snowmelt, *Hydrol. Processes*, 20, 923-941, 2006.**
- 695

- Pomeroy, J. W., Fang, X., and Ellis, C.: Sensitivity of snowmelt hydrology in Marmot Creek, Alberta, to forest cover disturbance. *Hydrol. Processes*, 26(12), 1891–1904, 2012.
- Pomeroy, J. W., Spence, C., and Whitfield, P. H.: Putting prediction in ungauged basins into practice, Canmore, Alberta, Canadian Water Resources Association, 1–12, 2013.
- 700 Pomeroy, J. W., Fang, X., and Rasouli, K.: Sensitivity of snow processes to warming in the Canadian Rockies, 72nd Eastern Snow Conference, Sherbrooke, Québec, Canada, 22–33, 2015.
- Rasouli, K.: Sensitivity analysis of mountain hydrology to changing climate, Ph.D. Dissertation, University of Saskatchewan, Saskatoon, Canada, pp. 251, 2017.
- Rasouli, K., Pomeroy, J. W., Janowicz, J. R., Carey, S. K., and Williams, T. J.: Hydrological sensitivity of a northern mountain basin to climate change, *Hydrol. Process.*, 28 (14), 4191–4208, 2014.
- 705 Rasouli, K., Pomeroy, J. W., and Marks, D. G.: Snowpack sensitivity to perturbed climate in a cool mid-latitude mountain catchment, *Hydrol. Process.*, 29 (18), 3925–3940, 2015.
- Rasouli, K., Pomeroy, J. W., and Whitfield, P. H.: Hydrological responses of headwater basins to perturbed climate in North American Cordillera, *J. Hydrometeorol.*, 20 (5), 863–882, <https://doi.org/10.1175/JHM-D-18-0166.1>, 2019a.
- 710 Rasouli, K., Pomeroy, J. W., Janowicz, J. R., Williams, T.J., and Carey, S. K.: A long-term hydrometeorological dataset (1993–2014) of a northern mountain basin: Wolf Creek Research Basin, Yukon Territory, Canada, *Earth Syst. Sci. Data*, 11(1), 89–100, 2019b.
- Rawlins, M. A., Steele, M., Serreze, M. C., Vörösmarty, C. J., Ermold, W., Lammers, R. B., McDonald, K. C., Pavelsky, T. M., Shiklomanov, A., and Zhang, J.: Tracing freshwater anomalies through the air-land-ocean system: A case study from the Mackenzie river basin and the Beaufort Gyre, *Atmosphere-Ocean*, 47 (1), 79–97, 2009.
- 715 Reba, M. L., Marks, D., Seyfried, M., Winstral, A., Kumar, M., and Flerchinger, G.: A long-term data set for hydrologic modeling in a snow-dominated mountain catchment, *Water Resour. Res.*, 47(7), W07702, doi:10.1029/2010WR010030, 2011.
- Reiners, W., Bouwman, A., Parsons, W., and Keller, M.: Tropical rain forest conversion to pasture: changes in vegetation and soil properties, *Ecol. Appl.*, 4 (2), 363–377, 1994.
- 720 Rodriguez-Iturbe, I.: Ecohydrology: A hydrologic perspective of climate-soil-vegetation dynamics, *Water Resour. Res.*, 36 (1), 3–9, 2000.
- Schneider, R. R.: Alberta's natural subregions under a changing climate: past, present, and future, Alberta Biodiversity Monitoring Institute, Edmonton, Canada, pp. 86, 2013.
- Schneider, R. R., Hamann, A., Farr, D., Wang, X., and Boutin, S.: Potential effects of climate change on ecosystem distribution in Alberta, *Can. J. For. Res.*, 39 (5), 1001–1010, 2009.
- 725 Seyfried, M., Grant, L., Marks, D., Winstral, A., and McNamara, J.: Simulated soil water storage effects on streamflow generation in a mountainous snowmelt environment, Idaho, USA, *Hydrol. Process.*, 23 (6), 858–873, 2009.

- 730 Smith, C. D.: April. The relationship between snowfall catch efficiency and wind speed for the Geonor T-200B precipitation gauge utilizing various wind shield configurations, In Proc. 77th Western Snow Conference, 115–121, Canmore, Alberta, Canada, April 20-23, 2009.
- Stanton, M., Rejmanek, M., and Galen C.: Changes in vegetation and soil fertility along a predictable snowmelt gradient in the Mosquito Range, Colorado, USA, *Arctic Alp. Res.*, 364–374, 1994.
- 735 Stow, D. A., Hope, A., McGuire, D., Verbyla, D., Gamon, J., Huemmrich, F., Houston, S., Racine, C., Sturm, M., Tape, K., et al.: Remote sensing of vegetation and land-cover change in Arctic Tundra Ecosystems, *Remote Sens. Environ.*, 89 (3), 281–308, 2004.
- Sturm, M., Schimel, J., Michaelson, G., Welker, J. M., Oberbauer, S. F., Liston, G. E., Fahnestock, J., and Romanovsky, V. E.: Winter biological processes could help convert arctic tundra to shrubland, *Bioscience*, 55 (1), 17–26, 2005.
- Sunyer, M., Madsen, H., and Ang, P.: A comparison of different regional climate models and statistical downscaling methods for extreme rainfall estimation under climate change, *Atmos. Res.*, 103, 119–128, 2012.
- 740 Tape, K., Sturm, M., and Racine, C.: The evidence for shrub expansion in northern Alaska and the Pan-Arctic, *Glob. Chang. Biol.*, 12 (4), 686–702, 2006.
- Tukey, J. W.: The philosophy of multiple comparisons, *Stat. Sci.*, 6(1), 100–116, 1991.
- Walker, D., Halfpenny, J. C., Walker, M. D., and Wessman, C. A.: Long-term studies of snow-vegetation interactions, *BioScience*, 43 (5), 287–301, 1993.
- 745 Walvoord, M. A. and Kurylyk, B. L.: Hydrologic impacts of thawing permafrost—A review, *Vadose Zone J.*, 15 (6), doi:10.2136/vzj2016.01.0010, 2016.
- Wilcoxon, F.: Individual comparisons by ranking methods, *Biometrics Bulletin*, 1 (6), 80–83, 1945.
- Williams, T. J., Pomeroy, J. W., Janowicz, J. R., Carey, S. K., Rasouli, K., and Quinton, W. L.: A radiative–conductive–convective approach to calculate thaw season ground surface temperatures for modelling frost table dynamics, *Hydrol. Process.*, 750 29(18), 3954–3965, 2015.
- Winstral, A. and Marks, D.: Long-term snow distribution observations in a mountain catchment: Assessing variability, time stability, and the representativeness of an index site, *Water Resour. Res.*, 50 (1), 293–305, 2014.
- Zhang, Y., Carey, S. K., and Quinton, W. L.: Evaluation of the algorithms and parameterizations for ground thawing and freezing simulation in permafrost regions, *J. Geophys. Res. Atmos.*, 113 (D17), doi: 10.1029/2007JD009343, 2008.
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Tables:

**Table 1.** Comparison of physiography and climatology amongst the three basins. UC denotes Upper Clearing meteorological station in Marmot Creek Research Basin.

<b>Characteristics</b>	<b>Wolf Creek</b>	<b>Marmot Creek</b>	<b>Reynolds Mountain</b>
Latitude	60°36' N	50°57' N	43°11' N
Longitude	134°57' W	115°09' W	116°47' W
Drainage area [km <sup>2</sup> ]	179	9.4	0.38
Elevation range [m]	660 – 2080	1600 – 2825	2028 – 2137
Record period	1993 – 2011	2005 – 2014	1983 – 2008
Dominant vegetation cover			
<i>high elevation</i>	tundra moss,	rock, grass	grass, sage
<i>middle elevation</i>	shrub tundra	spruce, fir	fir
<i>low elevation</i>	spruce	lodgepole pine	aspen, willow
Climate zone	Cordillera & sub-Arctic	Cordillera & Prairie & Boreal	Cordillera & Continental & Mediterranean
Elevation bands	3	3	1
Temperature [°C]			
<i>high elevation</i>	-3.4	-1.8	5.0
<i>middle elevation</i>	-2.0	1.0 (UC)	-
<i>low elevation</i>	-1.5	2.9	-
Number of Freezing days			
<i>high elevation</i>	224	217	120
<i>middle elevation</i>	203	166 (UC)	
<i>low elevation</i>	179	128	
Precipitation [mm]	380	1011	858
Wind speed [ms <sup>-1</sup> ]	3.7	5.8	1.9
Relative humidity [%]	74	69	61
Number of sub-basins & HRUs	5 & 29	4 & 36	1 & 12
HRU area range [km <sup>2</sup> ]	0.92 – 25.4	0.01 – 1.37	0.01 – 0.07

**Table 2.** Description of the eight cases of change in climate, vegetation, and soils.

<b>Climate</b>	<b>Vegetation and Soil Case</b>	<b>Notation used in text</b>	<b>Actual Change</b>
present	present vegetation, and present soil	Base	no change
present	future vegetation, present soil	$\Delta V$	only vegetation
present	present vegetation, future soil	$\Delta S$	only soil
present	future vegetation, future soil	$\Delta VS$	both vegetation & soil
future	present vegetation, present soil	$\Delta C$	only climate
future	future vegetation, present soil	$\Delta CV$	both vegetation & climate
future	present vegetation, future soil	$\Delta CS$	both soil and climate
future	future vegetation, future soil	$\Delta CVS$	climate, vegetation, & soil

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**Table 3.** Simulated **basin-scale** snow characteristics under current climate and future vegetation and soil **for the** three basins. Underlined values denote significant changes

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with  $p$ -values less than 0.1. Changes relative to current climate/vegetation/soil **and** are given in parentheses.

Variable	Current Climate												
	Current Vegetation & Soil		$\Delta$ Soil	$\Delta$ Vegetation	$\Delta$ Soil&Vegetation								
<b>(1) Wolf Creek</b>													
Peak SWE [mm]	133		133	118-133(-11 to 0)	118-133(-11 to 0)								
Initiation [date]	5		5	5(0)	5(0)								
Peak SWE [date]	186		186	182-185(-4 to -1)	182-185(-4 to -1)								
Snow-free [date]	250		250	250-252(0 to 2)	250-252(0 to 2)								
Season length [day]	224		224	224-226(0 to 2)	224-226(0 to 2)								
<b>(2) Marmot Creek</b>													
Peak SWE [mm]	183		183	<u>136-168(-26 to -8)</u>	<u>136-168(-26 to -8)</u>								
Initiation [date]	9		9	9(0)	9(0)								
Peak SWE [date]	210		210	211(1)	211(1)								
Snow-free [date]	294		294	294-296(0 to 2)	294-296(0 to 2)								
Season length [day]	283		283	283-284(0 to 1)	283-284(0 to 1)								
<b>(3) Reynolds Mountain</b>													
Peak SWE [mm]	368		368	326-375(-11 to 2)	326-375(-11 to 2)								
Initiation [date]	35		35	35(0)	35(0)								
Peak SWE [date]	161		161	162-168(1 to 7)	162-168(1 to 7)								
Snow-free [date]	246		246	247(1)	247(1)								
Season length [day]	211		211	212-213(1 to 2)	212-213(1 to 2)								
Day of Water Year	1 <sup>st</sup> of	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
		1	32	62	93	124	152	183	213	244	274	305	336

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**Table 4.** Simulated snow characteristics under current and monthly perturbed climate and future vegetation and soil in the three basins. Bold and underlined values denote significant changes with *p*-values less than 0.05 and 0.1, respectively. Changes, which are relative to current climate/vegetation/soil, are given in parentheses. Dates are given in water year days.

Variable	Base	ΔClimate			ΔClimate+			ΔClimate+			ΔClimate+		
	mean	Current Vegetation & Soil			ΔSoil			ΔVegetation			ΔSoil & ΔVegetation		
		5 %	mean	95 %	5 %	mean	95 %	5 %	mean	95 %	5 %	mean	95 %
<b>(1) Wolf Creek</b>													
Peak SWE [mm]	133	73	118 (-11)	153	73	118 (-11)	153	64	<b>107 (-20)</b>	142	64	<b>107 (-20)</b>	142
Initiation [date]	5	0	7 (2)	47	0	7 (2)	47	0	7 (2)	45	0	7 (2)	45
Peak SWE [date]	186	143	<b>164 (-22)</b>	178	143	<b>164 (-22)</b>	178	148	<b>164 (-22)</b>	170	148	<b>164 (-22)</b>	170
Snow-free [date]	250	213	<b>235 (-15)</b>	248	213	<b>235 (-15)</b>	248	216	<b>236 (-14)</b>	249	216	<b>236 (-14)</b>	249
Season length [day]	224	160	<b>208 (-16)</b>	242	160	<b>208 (-16)</b>	242	164	<b>215 (-9)</b>	251	164	<b>215 (-9)</b>	251
<b>(2) Marmot Creek</b>													
Peak SWE [mm]	183	102	<b>141 (-23)</b>	170	102	<b>141 (-23)</b>	170	74	<b>106 (-42)</b>	130	74	<b>106 (-42)</b>	130
Initiation [date]	9	4	<b>24 (15)</b>	62	4	<b>24 (15)</b>	62	4	<b>24 (15)</b>	63	4	<b>24 (15)</b>	63
Peak SWE [date]	210	175	<u>200 (-10)</u>	216	175	<u>200 (-10)</u>	216	177	205 (-5)	223	177	205 (-5)	223
Snow-free [date]	294	257	<b>281 (-13)</b>	295	257	<b>281 (-13)</b>	295	257	<b>283 (-11)</b>	299	257	<b>283 (-11)</b>	299
Season length [day]	283	204	<b>248 (-35)</b>	277	204	<b>248 (-35)</b>	277	200	<b>246 (-37)</b>	276	200	<b>246 (-37)</b>	276
<b>(3) Reynolds Mountain</b>													
Peak SWE [mm]	368	105	<b>196 (-47)</b>	277	105	<b>196 (-47)</b>	277	91	<b>168 (-54)</b>	237	91	<b>168 (-54)</b>	237
Initiation [date]	35	20	<b>50 (15)</b>	85	20	<b>50 (15)</b>	85	19	<b>49 (14)</b>	83	19	<b>49 (14)</b>	83
Peak SWE [date]	161	102	<b>129 (-33)</b>	148	102	<b>129 (-33)</b>	148	96	<b>127 (-34)</b>	149	96	<b>127 (-34)</b>	149
Snow-free [date]	246	184	<b>213 (-33)</b>	232	184	<b>213 (-33)</b>	232	195	<b>220 (-26)</b>	236	195	<b>220 (-26)</b>	236
Season length [day]	211	113	<b>161 (-50)</b>	197	113	<b>161 (-50)</b>	197	129	<b>171 (-40)</b>	200	129	<b>171 (-40)</b>	200
1 <sup>st</sup> of	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	
Day of Water Year	1	32	62	93	124	152	183	213	244	274	305	336	

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783 **Table 5.** Simulated runoff characteristics including annual volume under current and monthly perturbed climates and future vegetation in the three basins. Bold and under-  
784 lined values denote significant changes with  $p$ -values less than 0.05 and 0.1, respectively, based on the Mann-Whitney U-test. Simulated distributions with  $n = 18$  years for  
785 **Wolf Creek, 9 years for Marmot Creek, and 25 years for Reynolds Mountain over the present (base case)** period for each hydrological variable are compared with the simu-  
786 lated future distributions obtained from eleven regional climate models ( $11 \times n$  values). Percentage change, which are relative to the current climate/vegetation, are given in  
787 parentheses.

<b>Change Case</b>		<b>Wolf Creek</b>	<b>Marmot Creek</b>	<b>Reynolds Mountain</b>
No change	Base	246	402	371
Future vegetation	$\Delta V$	228-262 (-7 to +7)	<u>336-373(-16 to -7)</u>	340-379(-8 to +2)
Future soil	$\Delta S$	210 (-15)	<u>335 (-17)</u>	331 (-11)
Future soil & vegetation	$\Delta VS$	<b>173 (-30)</b>	411 (2)	365 (-2)
Future climate	$\Delta C$	286 (16)	426 (6)	375 (1)
Future climate and vegetation	$\Delta VC$	265 (8)	<u>359 (-11)</u>	351 (-5)
Future climate and soil	$\Delta SC$	250 (2)	414 (3)	342 (-8)
Future climate, soil & vegetation	$\Delta CVS$	282 (15)	<b>492 (22)</b>	368 (-1)
Number of simulation years		18	9	25

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