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 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).

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).

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.

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 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).

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).

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.

2 Methods

2.1 Study sites and data sources

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).

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). 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).

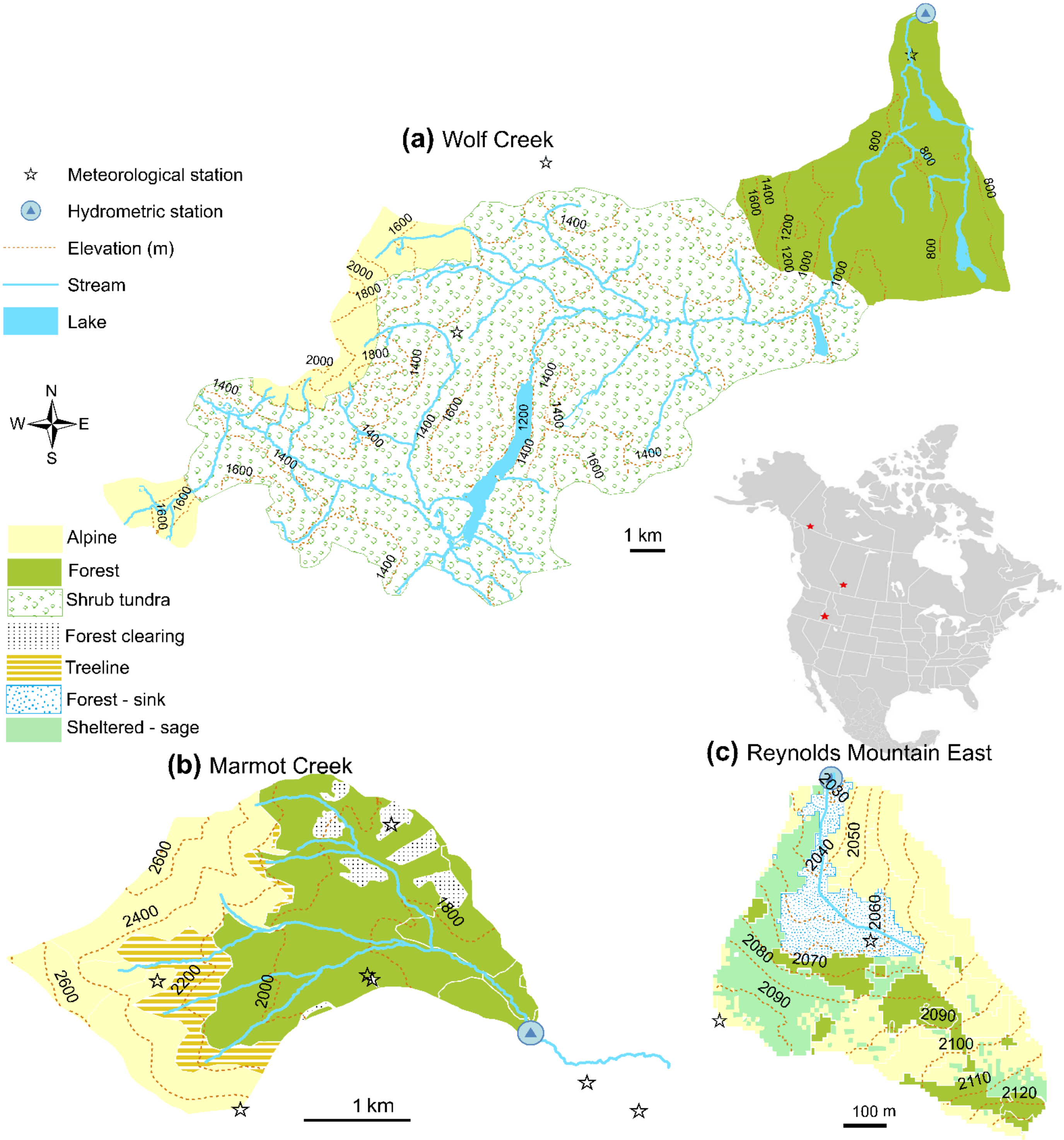

Figure 1. Vegetation, hydrography, topography, and meteorological stations of the three headwater study basins: **(a)** Wolf Creek Research Basin, Yukon Territory, Canada; **(b)** Marmot Creek Research Basin, Alberta, Canada; and **(c)** Reynolds Mountain within Reynolds Creek Experimental Watershed,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

2.2 Modelling strategy

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 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).

Eight change cases were used to differentiate the individual and combined effects of changes in climate (ΔC), vegetation (ΔV), and soils (ΔS) 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 (ΔVS), (2) climatic conditions change but no changes in future vegetation and/or soil occur (ΔC), and (3) changes in future climate will be accompanied by vegetation and soil changes (ΔCV, ΔCS, and ΔCVS). 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 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 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 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.

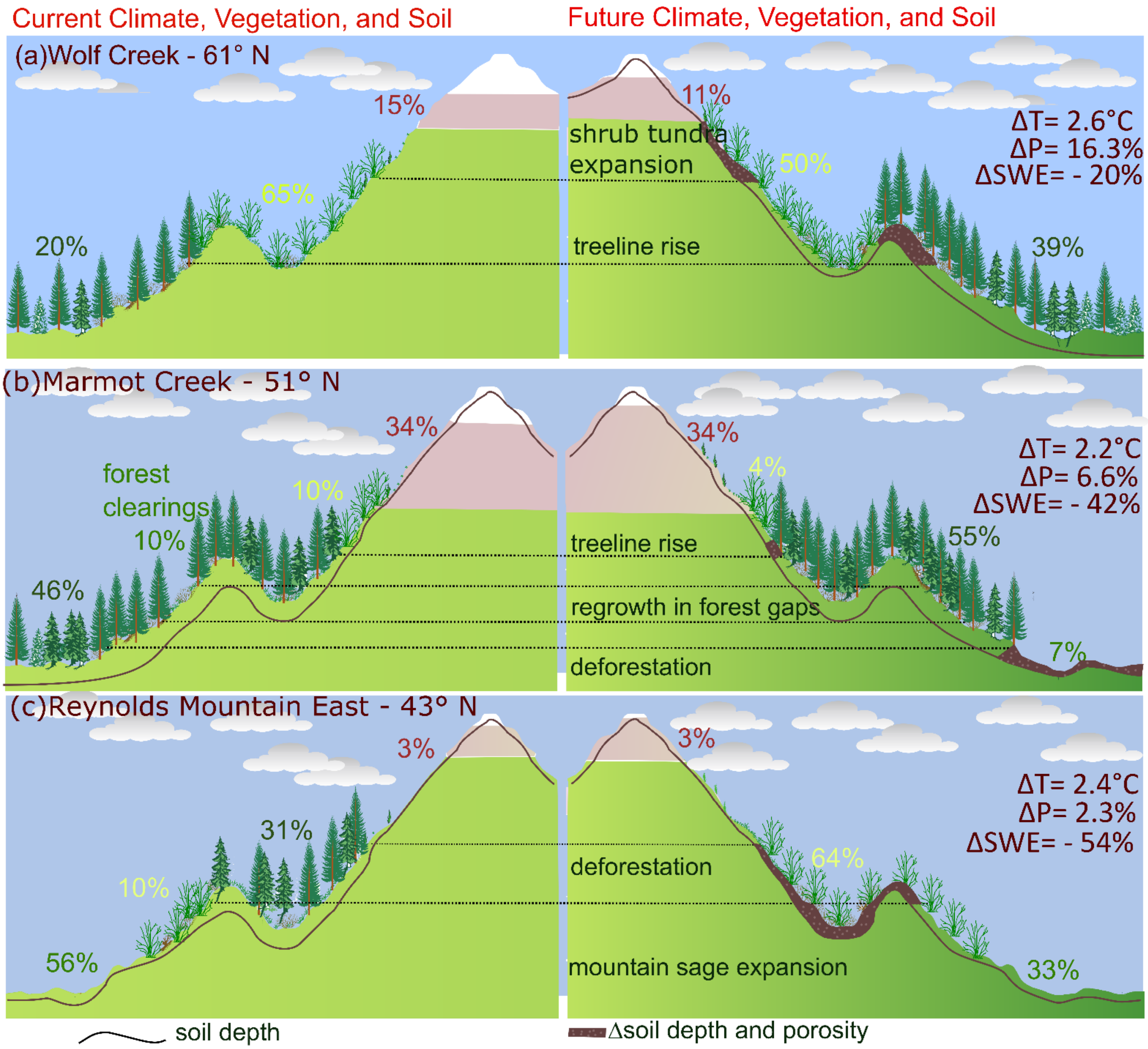

Figure 2. Schematic illustration of the vegetation cover under base case and future climate, vegetation, and soil (ΔCVS) in Wolf Creek Research Basin, Marmot Creek Research Basin, and Reynolds Mountain. Dark shading indicates areas where changes to soil are expected in future. The numbers show the areal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

2.3 Perturbed observations

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 (ΔC), vegetation (ΔV), and soil (ΔS) 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 ($x^{c}_{1:11\times n}$,$11\ \times n$ values) and the simulated distributions in the modelled future periods, obtained for eleven RCMs ($x^{f}_{1:11\times n}$,$11\ \times n$ 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 (ΔV, ΔS, and ΔVS) 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).

In Wolf Creek (Figure 3), the peak SWE declined significantly with ΔC (group "a") in the alpine biome (Fig. 3a), and increased insignificantly with ΔV and ΔVS in the present climate. Peak SWE decreased significantly with ΔC, ΔCV, ΔCS, and ΔCVS (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 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 ΔV, ΔS, and ΔVS change cases in the present climate and increases significantly for the future climate ΔC, and ΔCS cases (Fig. 3d). The decrease in annual runoff with soil and vegetation changes (ΔV, ΔS and ΔVS) 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 (ΔCV and ΔCVS) 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 (ΔC), (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 ΔV and ΔVS and in the forest clearing also with climate changes and all case combinations (groups "a" and b", Fig. 4c, Fig. 4d). Soil changes alone (ΔS) do not affect peak SWE in Marmot Creek. The annual runoff volume in Marmot Creek decreases with ΔV and ΔVS and increases with ΔCS (Fig. 4e). This counteracting behavior is evident in the response of annual runoff to ΔC and ΔCVS, which is not significantly different from the base case (all are in group "b"). In contrast, the combined effect of climate and soil change (ΔCS is "c" in Fig. 4e) is magnified from that of climate alone. Therefore, soil-climate interactions (ΔCS) 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 (ΔC) (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 (ΔC) and soil (ΔCS) changes do not affect the annual runoff volume whilst vegetation change and combined vegetation and soil change (ΔV and ΔVS) significantly decrease annual 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).

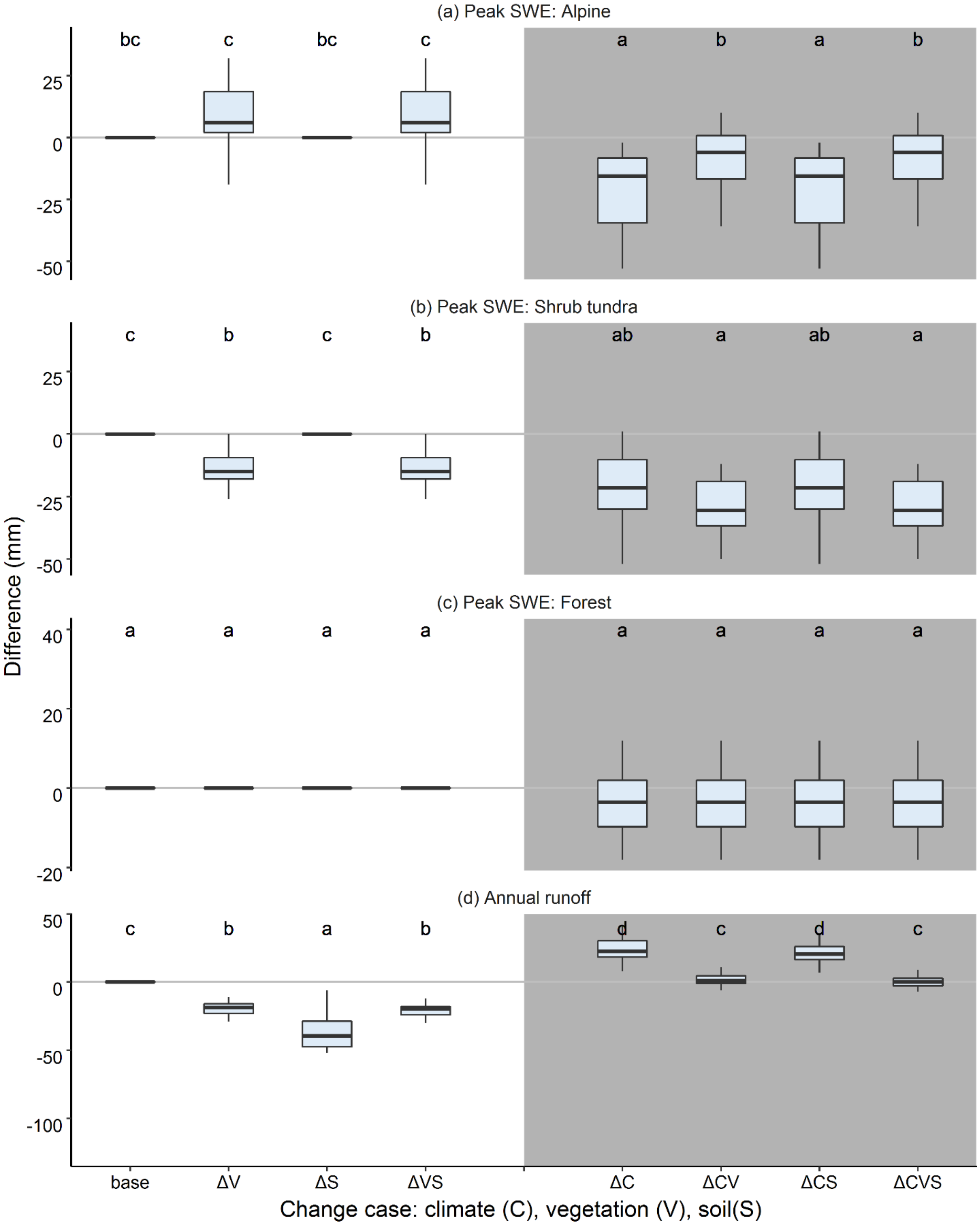

Figure 3. Differences in peak snow water equivalent (SWE) and annual runoff volume under seven combinations of changes in climate, vegetation, and soil in the Wolf Creek Research Basin relative to present climate, present vegetation, and present soil with no change (base). Lower case letters from Tukey's 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.

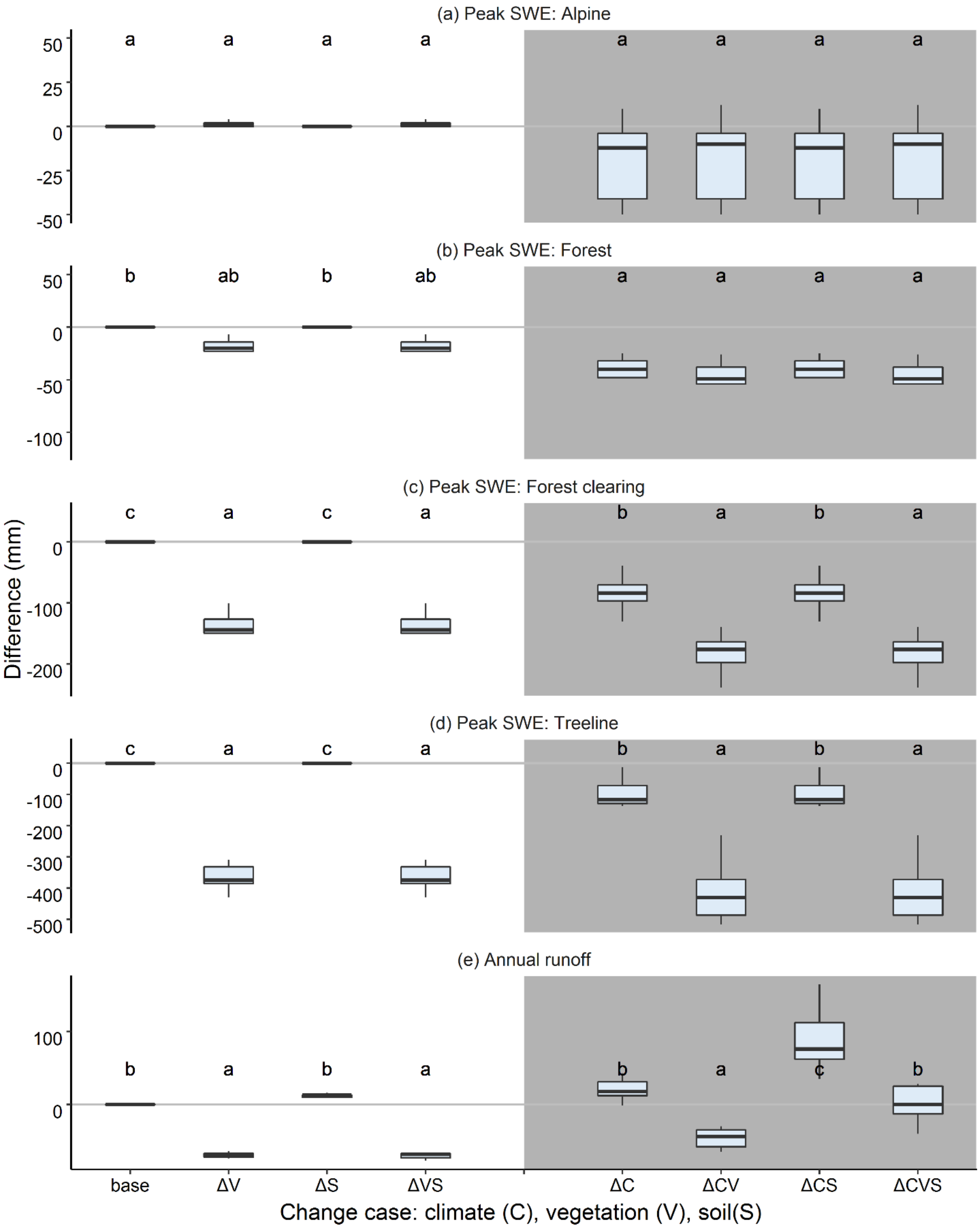

Figure 4. Differences in peak snow water equivalent (SWE) and annual runoff volume under seven combinations of changes in climate, vegetation, and soil in the Marmot Creek Research Basin relative to present climate, present vegetation, and present soil with no change (base). Lower case letters from Tukey's 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.

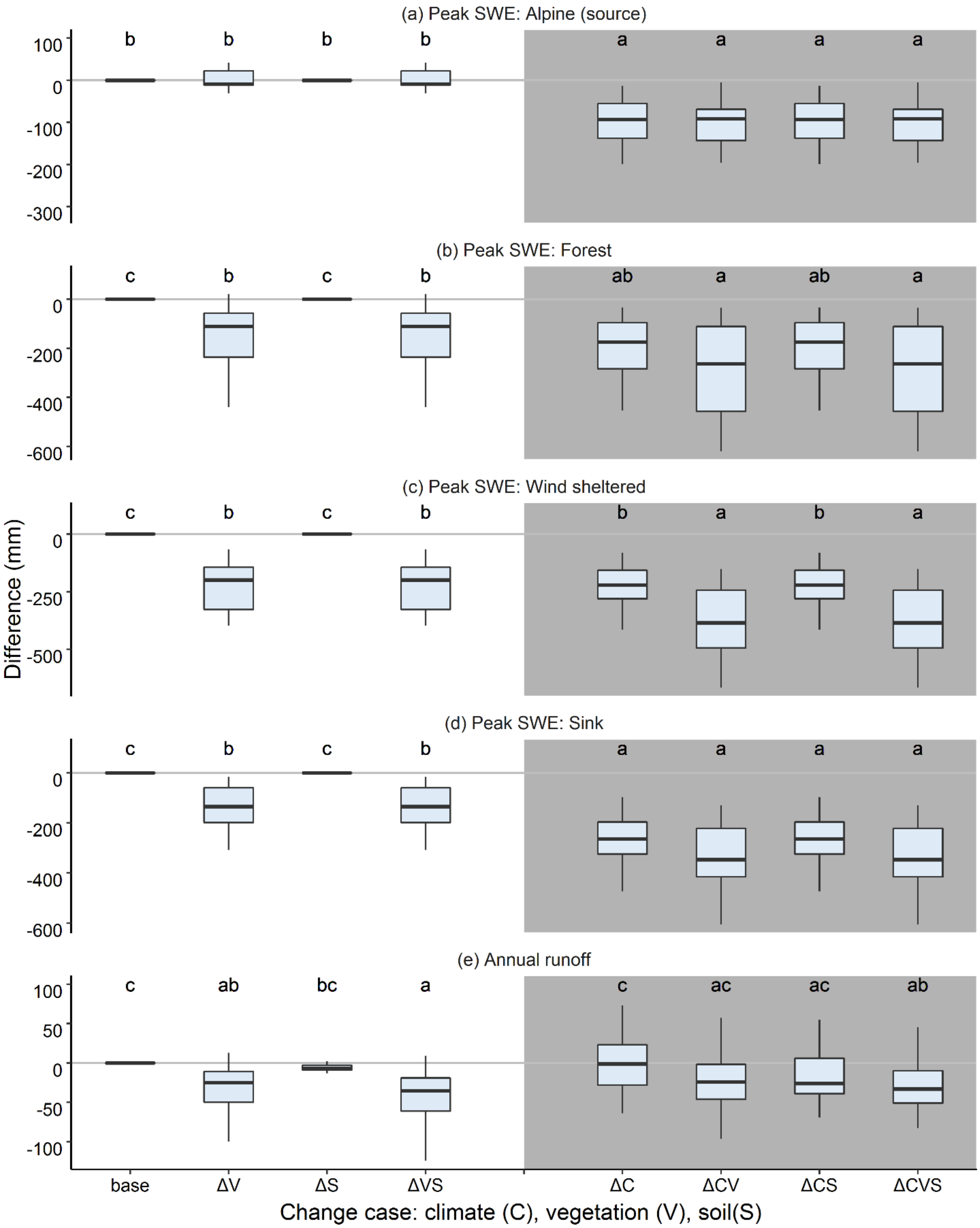

Figure 5. Differences in peak snow water equivalent (SWE) and annual runoff volume under seven combinations of changes in climate, vegetation, and soil in the Reynolds Mountain relative to present climate, present vegetation, and present soil with no change (base). Lower case letters from Tukey's HSD 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.

3.2 Snow characteristics

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 ≤ 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 (ΔV 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 ΔC, changed vegetation ΔV, and both changed climate and vegetation ΔCV cases with shading to reflect interannual variability. The simulated snowpack regimes for ΔC, ΔV, and ΔCV are significantly (p-value ≤ 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 ΔV, 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 ΔV, 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 curved during the ablation period in Figure 6. There is no change in the slope between the base case and ΔCV 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 ΔCV 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 ΔCV, 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 ΔCV, 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).

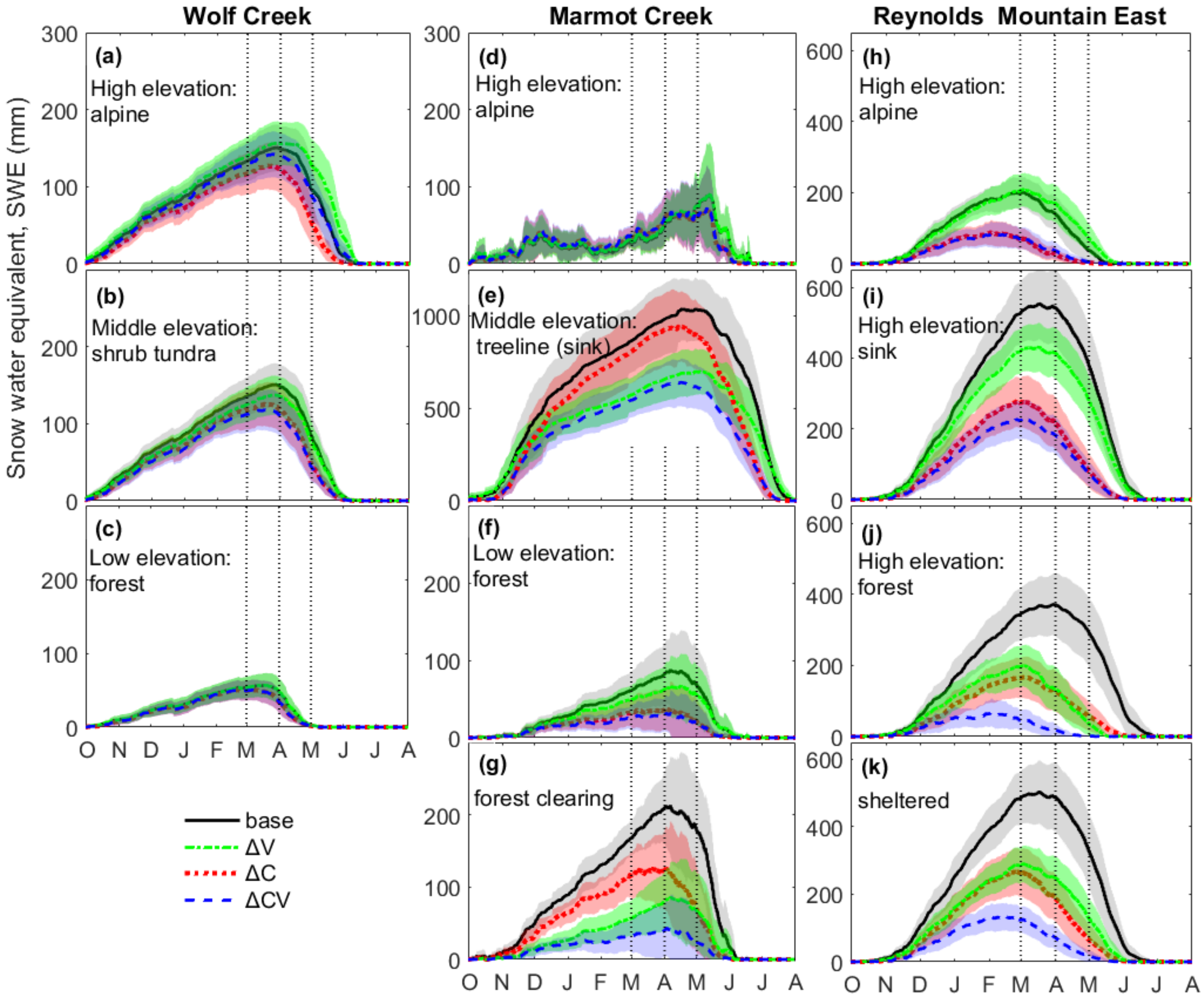

Figure 6. Simulated snowpack accumulation and ablation under current climate and vegetation (base scenario) and changes due to climate and vegetation changes in different elevation levels and current biomes in Wolf Creek Research Basin, Marmot Creek Research Basin, and Reynolds Mountain. Reynolds Mountain 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.

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 ΔV scenario (Fig. 6d). In contrast to greater snowpacks with upward movement of the treeline (ΔV), climate change alone (ΔC) 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 (ΔV) on reducing snowpacks is even greater than that of climate change (ΔC) (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 (ΔCV). 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 ΔV and advanced with only ΔC (Table 3).

In Reynolds Mountain, all blowing snow regimes except for the depressions and valley bottom (Fig. 6i) will receive a more uniform SWE under ΔV 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 ΔC on the snowpack in this biome is large (Fig. 6h). The forest biome in Reynolds Mountain is most sensitive to ΔCV, 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 ΔCV 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 ΔV.

Snow regimes are the most resilient to ΔCV 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 ΔCV, with 80% and 68% decreases, respectively due to the role of canopy changes enhancing climate change impacts in reducing SWE. Under ΔV, 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 ΔC on snow regimes can be enhanced or dampened by the impact of ΔV. 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 ΔC 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

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.

3.4 Snow Transport and Redistribution

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 ΔCV, 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 ΔC and increases 23 mm due to shorter fetches as the treeline moves upslope with concomitant vegetation change (ΔCV). 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 ΔC, 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 from 79 mm to 37 mm (42 mm decrease, p-value ≤ 0.05) under climate change and deforestation (ΔCV).

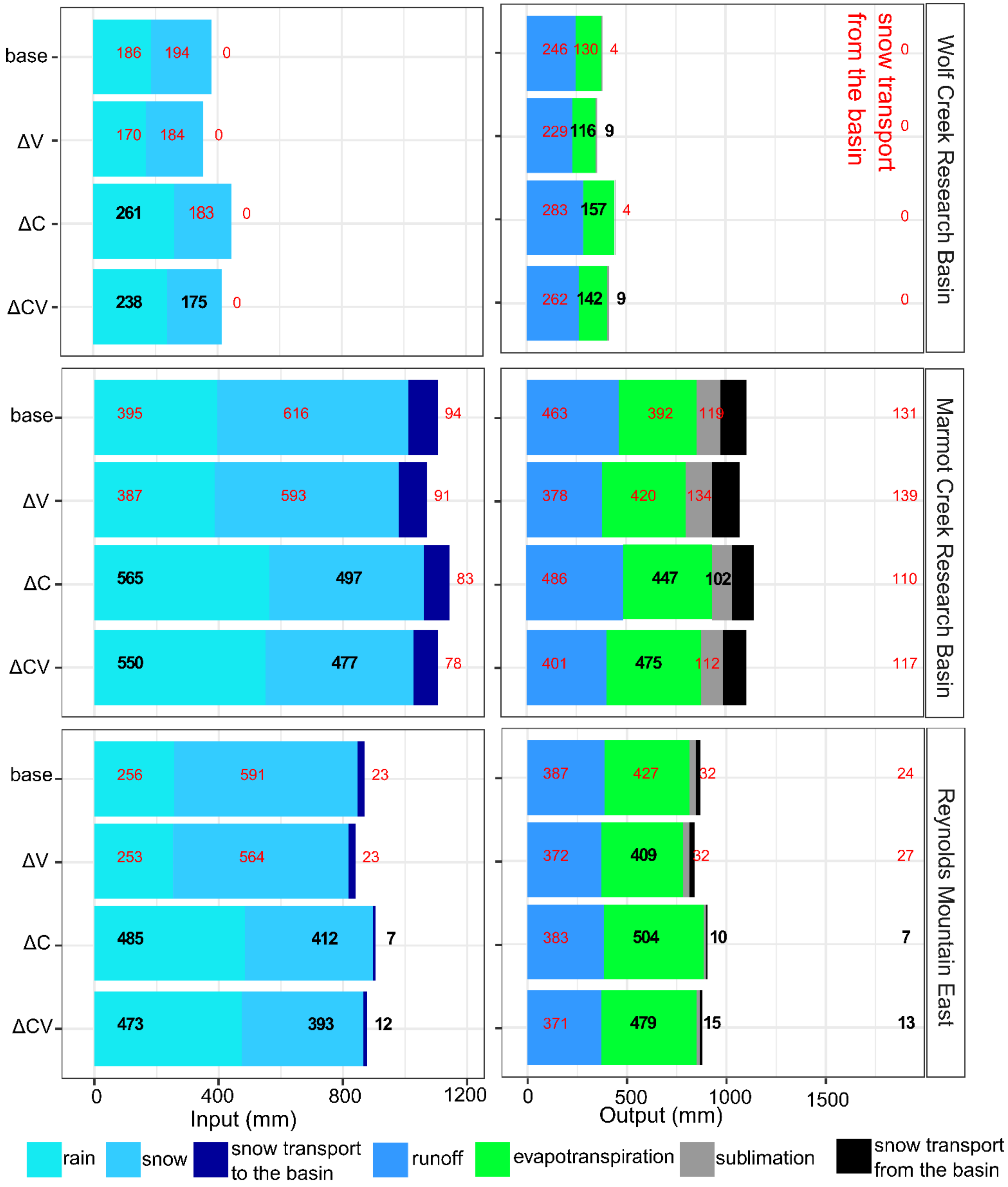

Figure 7. Mean modelled water fluxes, in three states of liquid, vapor, and snow, under current climate and current vegetation (base), future climate and current vegetation (ΔC), (c) current climate and future vegetation (ΔV), and future climate and future vegetation (ΔVC) in Wolf Creek Research Basin, 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.

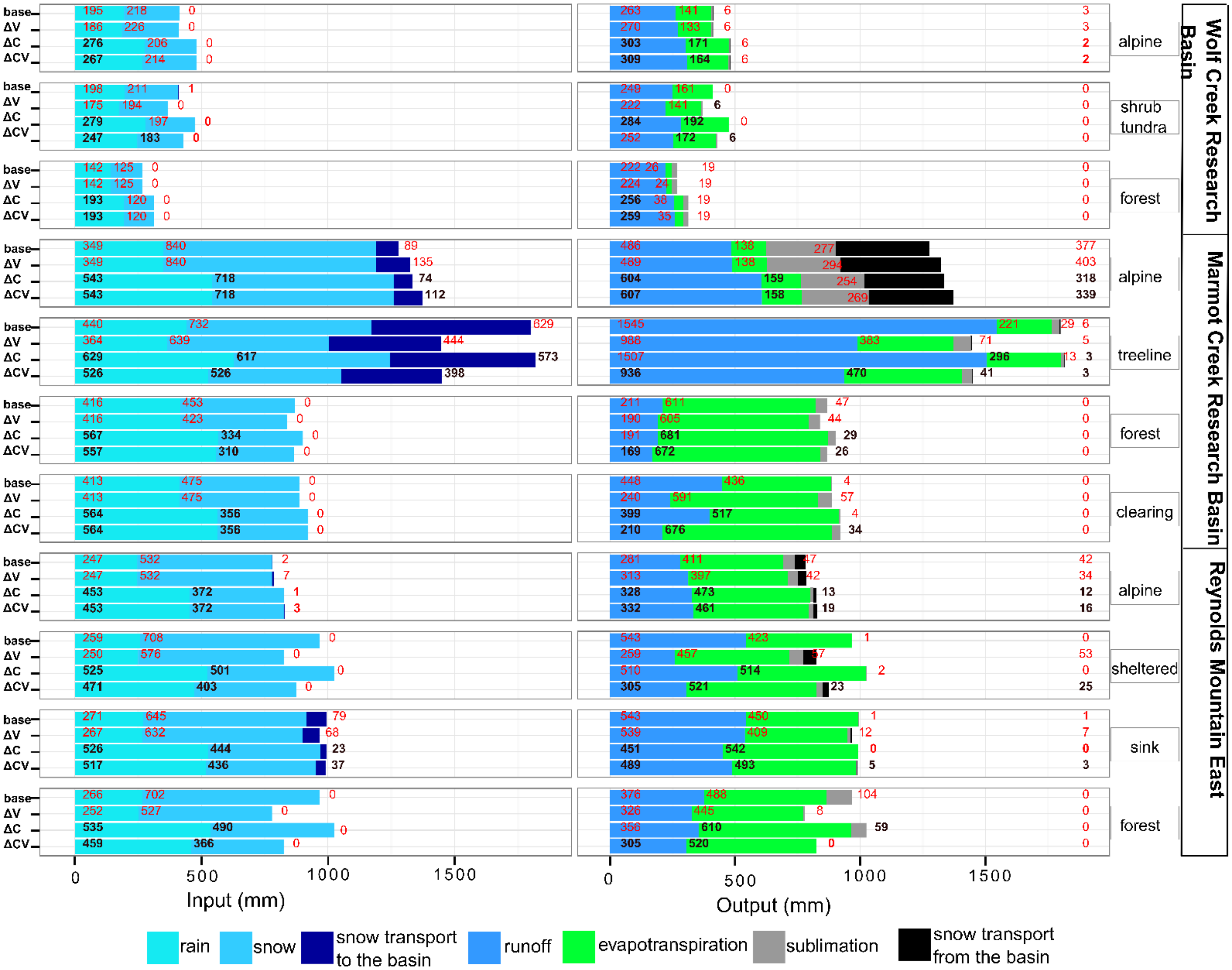

Figure 8. Mean modelled water fluxes, in three states of liquid, vapor, and snow, on an elevation/ vegetation basis under current climate and current vegetation (base), current climate and future vegetation (ΔV), future climate and current vegetation (ΔC), and future climate and future vegetation (ΔVC) 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.

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

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 ΔV but decreases 7 mm under ΔVC (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, ΔV causes sublimation to increase moderately in Marmot Creek and Wolf Creek basins due to enhanced sublimation of intercepted snow. Vegetation change does not affect sublimation in Reynolds Mountain.

3.6 Evapotranspiration (ET)

ΔV also alters the annual evapotranspiration (ET). The simulations show that, under ΔV, 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 ΔC 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 ΔVC, ET changes significantly in different elevation bands (Figure 8). The increase in ET due to ΔCV 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.

3.7 Runoff characteristics

ΔV 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 ΔVC, 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).

The average annual hydrographs for the present and future climates simulations under vegetation and soil changes are shown in Figure 9. With ΔV, high flows are lower in all three basins, particularly in Wolf Creek (Fig. 9a). ΔC 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 (ΔC) and soil changes (ΔS) do not cause significant changes in annual runoff volumes in Marmot Creek and Reynolds Mountain, while in Wolf Creek climate change (ΔC) increases and soil change (ΔS) decreases the annual runoff volume (246 to 210mm, Table 4, Fig. 3d). The combined effect of climate – vegetation change (ΔCV) 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). ΔCV delayed the snow accumulation initiation date by 15 days in Marmot Creek and 14 days in Reynolds Mountain. The beginning of the melt season under ΔCV, 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).

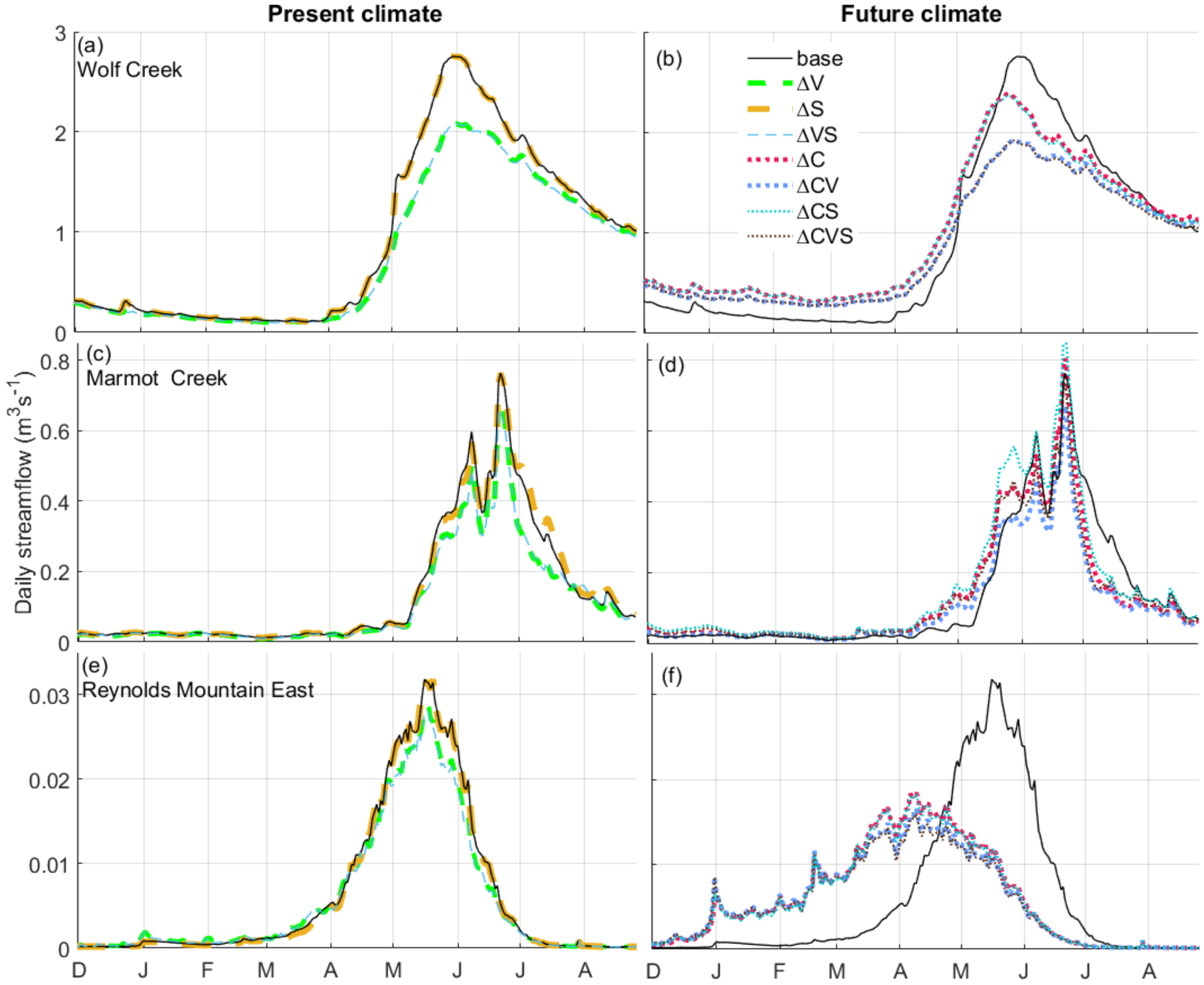

Figure 9. Annual average hydrographs under present climate, present vegetation, and present soil (base), present climate, future vegetation, present soil (ΔV), present climate, present vegetation, future soil (ΔS), present climate, future vegetation, future soil (ΔVS), future climate, present vegetation, present soil (ΔC), future climate, future vegetation, present soil (ΔCV), future climate, present vegetation, future soil (ΔCS), and future climate, future vegetation, future soil (ΔCVS) in the three basins.

4 Discussion

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 ΔV can become important with concomitant climate change in that it can offset the climate change effect under ΔCV (Fig. 3a). ΔV decreases annual runoff in Wolf Creek while ΔC counteracts the effect of vegetation change and increases the annual runoff with ΔCV (Fig. 3d). The individual effects of soil (ΔS) and climate change (ΔC) on annual runoff in Marmot Creek are statistically insignificant, but when they are combined (ΔCS), 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 (ΔC) is offset by vegetation change effect (ΔCV) in Wolf Creek, and it is enhanced by soil change effect (ΔS) in Marmot Creek, while the effect of climate change (ΔC) on annual runoff in Reynolds Mountain is not significant, and the vegetation change (ΔV) 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 soil and climate change (ΔCVS 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).

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. Shrub expansion into higher elevations prolongs the snow season and increases peak 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 (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 (ΔCV case) in Marmot Creek (Fig. 4e), which is due to significant decreases in sublimation and snow transport and 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, 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 (ΔCVS) occur in Reynolds Mountain (Fig. 5e), climate – soil changes (ΔCS) occur in Marmot Creek (Fig. 4e), and soil – vegetation changes (ΔVS) 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.

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, 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).

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)

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.

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.

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 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.

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.

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.

Acknowledgments. We thank Danny Marks of USDA and the late Rick Janowicz of Yukon Environment who had a long-term commitment to operate and provide the data for Reynolds Mountain and Wolf Creek Research Basin, respectively. The research funding sources include the Canada Research Chairs programme, the Natural Sciences and Engineering Research Council of Canada through Discovery Grants, Alexander Graham Bell Canada Graduate Scholarship-Doctoral Program and Postdoctoral Fellowships, and the Changing Cold Regions Network. We thank Xing Fang for his help with modelling of Marmot Creek. The discussions and comments of Andrew Ireson and Lawrence Martz on an earlier draft of this paper are appreciated. The helpful comments and suggestions of two anonymous reviewers on the manuscript are appreciated.

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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.

Characteristics	**Wolf Creek**	**Marmot Creek**	**Reynolds Mountain**
Latitude	60◦36′N	50◦57′N	43◦11′N
Longitude	134◦57′W	115◦09′W	116◦47′W
Drainage area [km^2]	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			
high elevation	tundra moss,	rock, grass	grass, sage
middle elevation	shrub tundra	spruce, fir	fir
low elevation	spruce	lodgepole pine	aspen, willow
Climate zone	Cordillera & sub-Arctic	Cordillera & Prairie & Boreal	Cordillera & Continental & Mediterranean
Elevation bands	3	3	1
Temperature [◦C]			
high elevation	-3.4	-1.8	5.0
middle elevation	-2.0	1.0 (UC)	-
low elevation	-1.5	2.9	-
Number of Freezing days			
high elevation	224	217	120
middle elevation	203	166 (UC)	
low elevation	179	128	
Precipitation [mm]	380	1011	858
Wind speed [ms^{-1}]	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^2]	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.

Climate	Vegetation and Soil Case	Notation used in text	Actual Change
present	present vegetation, and present soil	Base	no change
present	future vegetation, present soil	ΔV	only vegetation
present	present vegetation, future soil	ΔS	only soil
present	future vegetation, future soil	ΔVS	both vegetation & soil
future	present vegetation, present soil	ΔC	only climate
future	future vegetation, present soil	ΔCV	both vegetation & climate
future	present vegetation, future soil	ΔCS	both soil and climate
future	future vegetation, future soil	ΔCVS	climate, vegetation, & soil

Table 3. Simulated basin-scale snow characteristics under current climate and future vegetation and soil for the three basins. Underlined values denote significant changes 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	Current Climate **ΔSoil**	Current Climate **ΔVegetation**	Current Climate **ΔSoil&Vegetation**
(1) Wolf Creek				
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)
(2) Marmot Creek				
Peak SWE [mm]	183	183	136-168(-26 to -8)	136-168(-26 to -8)
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)
(3) Reynolds Mountain				
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)

1st 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

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 Current Vegetation & Soil			ΔClimate+ ΔSoil			ΔClimate+ ΔVegetation			ΔClimate+ ΔSoil &ΔVegetation		
	mean	5 %	mean	95 %	5 %	mean	95 %	5 %	mean	95 %	5 %	mean	95 %
(1) Wolf Creek													
Peak SWE [mm]	133	73	118 (-11)	153	73	118 (-11)	153	64	**107 (-20)**	142	64	**107 (-20)**	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	**164 (-22)**	178	143	**164 (-22)**	178	148	**164 (-22)**	170	148	**164 (-22)**	170
Snow-free [date]	250	213	**235 (-15)**	248	213	**235 (-15)**	248	216	**236 (-14)**	249	216	**236 (-14)**	249
Season length [day]	224	160	**208 (-16)**	242	160	**208 (-16)**	242	164	**215 (-9)**	251	164	**215 (-9)**	251
(2) Marmot Creek													
Peak SWE [mm]	183	102	**141 (-23)**	170	102	**141 (-23)**	170	74	**106 (-42)**	130	74	**106 (-42)**	130
Initiation [date]	9	4	**24 (15)**	62	4	**24 (15)**	62	4	**24 (15)**	63	4	**24 (15)**	63
Peak SWE [date]	210	175	200 (-10)	216	175	200 (-10)	216	177	205 (-5)	223	177	205 (-5)	223
Snow-free [date]	294	257	**281 (-13)**	295	257	**281 (-13)**	295	257	**283 (-11)**	299	257	**283 (-11)**	299
Season length [day]	283	204	**248 (-35)**	277	204	**248 (-35)**	277	200	**246 (-37)**	276	200	**246 (-37)**	276
(3) Reynolds Mountain													
Peak SWE [mm]	368	105	**196 (-47)**	277	105	**196 (-47)**	277	91	**168 (-54)**	237	91	**168 (-54)**	237
Initiation [date]	35	20	**50 (15)**	85	20	**50 (15)**	85	19	**49 (14)**	83	19	**49 (14)**	83
Peak SWE [date]	161	102	**129 (-33)**	148	102	**129 (-33)**	148	96	**127 (-34)**	149	96	**127 (-34)**	149
Snow-free [date]	246	184	**213 (-33)**	232	184	**213 (-33)**	232	195	**220 (-26)**	236	195	**220 (-26)**	236
Season length [day]	211	113	**161 (-50)**	197	113	**161 (-50)**	197	129	**171 (-40)**	200	129	**171 (-40)**	200

1st 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

Table 5. Simulated runoff characteristics including annual volume under current and monthly perturbed climates and future vegetation in the three basins. Bold and underlined 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 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 simulated future distributions obtained from eleven regional climate models (11× *n* values). Percentage change, which are relative to the current climate/vegetation, are given in parentheses.

Change Case		**Wolf Creek**	**Marmot Creek**	**Reynolds Mountain**
No change	Base	246	402	371
Future vegetation	ΔV	228-262 (-7 to +7)	336-373(-16 to -7)	340-379(-8 to +2)
Future soil	ΔS	210 (-15)	335 (-17)	331 (-11)
Future soil & vegetation	ΔVS	**173 (-30)**	411 (2)	365 (-2)
Future climate	ΔC	286 (16)	426 (6)	375 (1)
Future climate and vegetation	ΔVC	265 (8)	359 (-11)	351 (-5)
Future climate and soil	ΔSC	250 (2)	414 (3)	342 (-8)
Future climate, soil & vegetation	ΔCVS	282 (15)	**492 (22)**	368 (-1)
Number of simulation years		18	9	25