Effects of climate and forest cover change on snowmelt dominated water supplies in the Okanagan

FFESC Project #16

Final Report, May 2012

Sarah Boon (University of Lethbridge)

Rita Winkler (BC Ministry of Forests, Lands and Natural Resource Operations)

John Pomeroy (University of Saskatchewan)

Dave Spittlehouse (BC Ministry of Forests, Lands and Natural Resource Operations)

1.0 Introduction

One of the most important ecosystem services from forested regions is the provision of a sustainable water supply. In the United States, for example, streamflow from forest land provides almost 2/3 of the total freshwater supply (Jones et al. 2009). On a global scale, forested headwaters that are snowmelt-dominated produce 60% of total runoff (Chang 2003). Given that forest ecosystems are significantly affected by climate change and associated forest disturbance such as wildfire, insect infestation, and disease (Westerling et al. 2006; Littell et al. 2009), there is a critical need to quantify the subsequent effect of these changes on water supply.

In British Columbia, the Forest and Range Practices Act (FRPA) requires the forest industry to incorporate non-timber values such as water into their forest management plans using best available knowledge. The response of snow processes to clearcut harvesting is well understood, and has been used as a forest management strategy to increase water yield from headwater basins (Hibbert 1967; Bethlalmy 1974; Ziemer et al. 1991; Wigmosta and Burges 2001). However, we know little about the effects of natural disturbance, such as mountain pine beetle (*Dendroctonus ponderosae*; MPB) and wildfire, and much of this more recent knowledge is at the stand rather than watershed scale (Winkler and Boon 2009; Bewley et al. 2010; Pugh and Small 2011; Schnorbus 2011). Our research expands previous stand-scale hydrologic process research to the source area watershed scale. The results provide forest and water resource professionals with key information required to assess the hydrologic consequences of forest response to climate change, and to make scientifically defensible water and timber management decisions.

The Okanagan Basin is semi-arid and heavily populated, with a high water demand for both agriculture and domestic consumption, and one of the lowest per capita water supplies in Canada (Cohen et al. 2006). Water supplies in the Okanagan Valley originate mainly from snow stored over winter in high elevation headwater basins, that is delivered downstream as surface water during spring melt. These headwaters are located in the Engelmann spruce-subalpine fir dry cold biogeoclimatic zone (ESSFdc), where forest cover has a major influence on seasonal snow accumulation and melt (Pomeroy et al. 2002; Winkler et al. 2005; Boon 2009). In response to scarce and seasonal water supplies, numerous small upland reservoirs have been constructed to store snowmelt runoff and maintain water availability throughout the year. Low snow years and limited storage capacity already result in water stress, challenging supply management not only for domestic and agricultural use, but also for aquatic habitat. Management approaches to mitigate the consequences of such water shortages include water use restrictions and the designation of fisheries-sensitive streams.

Predicted reductions in upper-elevation snow water yields have been identified as one of the most significant impacts of climate change in the Okanagan (Okanagan Water Stewardship Council 2008). Our research directly addresses the next stage of the OBWB's 'Water Supply and Demand' project, which is to improve our ability to accurately model both current snowpack processes in forested upland watersheds, and the effects of climate and forest change on snow water storage and release. A clear understanding of the effects of climate change on forested upland water supplies is essential for valley bottom water planning and is strongly linked with future community development, agricultural production, and the sustainability of aquatic ecosystems.

This project was a focused 2-year case study with clearly identified deliverables. The overall goal was to quantify the effects of climate and forest cover change on snow accumulation and melt processes in a forested high-elevation watershed at Upper Penticton Creek (UPCr) (Winkler et al., 2008) (Fig. A1; all figures and tables are included in Appendix 1 of this report). This critical area provides partial water supply for the City of Penticton and is representative of many headwater catchments in the Okanagan Basin. Using a long-term dataset from the UPCr watersheds – particularly the 25-year hydrometeorological record and 18-year snow accumulation record – we calibrated and validated a snow hydrology model (Cold Regions Hydrological Model; CRHM) developed at the University of Saskatchewan (Pomeroy et al. 2007).

Hydrologic modelling allows us to use field data to test and understand interactions between hydrological processes and the factors that control them over time and space in a simulated environment (Ziemer et al. 1991; Beckers et al. 2009). Models have previously been applied to quantify the impact of MPB and wildfire on snowmelt runoff response (van de Vosse 2008; Bewley et al. 2010; Seibert et al. 2010). While these studies generally agree that disturbance affects the timing and magnitude of snow accumulation and melt, they either: (a) used simplified representations of forest cover (Carver et al. 2009), or (b) analyzed the effect of post-disturbance forest management via salvage logging (Alila and Luo 2007), rather than focusing specifically on the disturbance itself. Thus, the application of models to quantify snow accumulation and melt response to forest disturbance has been limited despite the importance of this information for sound forest and water management (Seidl et al. 2010).

We used CRHM to assess the effects of changing air temperature, precipitation and forest cover (due to natural and anthropogenic disturbance) on snow accumulation and ablation. CRHM was particularly well suited to this application as it focuses on snow accumulation and ablation contributions to the hydrologic cycle in small to medium sized forested watersheds. Because it is module-based, the user is able to select those model parameters that are directly relevant to snowpack processes in the watersheds of interest. The model has accurately simulated snowmelt-generated runoff in prairie to boreal forests and mountain to muskeg hydrologic regimes (Pomeroy et al. 2007; Rutter et al. 2009). This was its first application in the BC interior.

This research aimed to resolve high priority issues in water management as identified by the project clients (Ministry of Forests, Lands and Natural Resource Operations, Okanagan Basin Water Board, Ministry of Healthy Living and Sport, Ministry of Environment, Okanagan Nation Alliance). Throughout the project, we collaborated with these clients to interpret research results in the broader context of potential community impacts and adaptations under predicted future water supply scenarios. To date, no detailed process-based snow water delivery models have been applied to upland snowmelt-dominated watersheds in the Okanagan Basin. The validation of CRHM in this case study thus forms the basis for its future application to other watersheds throughout the Okanagan region. Results can inform foresters and policy makers of the water supply implications of forest management practices in snow-dominated source areas, and provide science-based support for forest policy development aimed at maintaining high environmental standards and sustaining water supplies from the forest land base as climate changes.

2.0 Research Process: Objectives

(1) Establish a working group comprised of water purveyors, community leaders, government agencies, and experts in the fields of climate change, forest hydrology, and water management to identify uncertainties regarding forested upland water supplies, the most probable climate and forest cover changes at high elevations, and the potential land management responses to these changes in order to steer the modelling component of the project;

(2) Collate and quality assure existing long-term datasets from the UPCr study area for use in model calibration, validation, and scenario runs;’

(3) Collect additional snowpack and radiation transmittance data required as model input and currently unavailable;

(4) Calibrate and validate the CRHModel at UPCr using baseline (historical) conditions;

(5) Use climate change scenarios for the region to model potential climate change impacts on snow hydrology and water supply under existing forest cover;

(6) Use forest disturbance scenarios to model forest cover change impacts on snow hydrology and water supply;

(7) Present model results to the working group and collaborate with them to assess possible community and regional adaptations to research results; and,

(8) Provide tools (i.e., CRHM and model output) for incorporating the results into future broader water supply assessments throughout the Okanagan Basin.

3.0 Research Process: Approach and Methods

A scientific summary of the research methods, including field sampling methods and an overview of CRHM, is provided in Appendix 2. At the time of interim report submission in November 2010, we had completed the first three objectives. We held our first meeting with the working group, collated all required datasets (streamflow, meteorological data, snow surveys, forest surveys, soil moisture and channel surveys), and collected additional data as required for the project (snow surveys, sub-canopy radiation data). The graduate student we hired (Reed Davis) was working with the modelling team to learn how to apply CRHM to UPCk given the available data. Since then, the remaining objectives were achieved in stages as outlined below.

1. *Baseline model run*

   The model was run for the period 1 Oct 1999-30 June 2008 using hourly meteorological data (air temperature, relative humidity, precipitation, solar radiation, wind speed) from one weather station in the watershed as input. Model parameters, defined from field data and observations, included topographic variables (elevation, slope, aspect), air temperature and precipitation lapse rates, snow albedo, and canopy structure (leaf area index (LAI) and tree height). Model outputs of snow water equivalent (SWE) in a mature forest and in a clearcut were statistically compared with measured SWE from the same time period and forest type to quantify the accuracy of model simulations.

2. *Climate sensitivity tests*

   Key climate change projections for the Okanagan region were acquired from Cohen et al. (2006). These scenarios suggest winter precipitation increases of up to +30%, and winter air temperature increases of up to 4ºC. These changes were applied incrementally to the model input dataset for 2002-2003 only, as it was a high snow year that would be fairly sensitive to projected changes in temperature and precipitation. We conducted three tests: air temperature increases in increments of 0.5ºC, precipitation increases in increments of 5%, and combined air temperature and precipitation increases in increments of 1ºC/10%. We then examined model output to determine the sensitivity of the system to climate shifts, specifically the timing and magnitude of peak snow accumulation, the timing and rate of snowmelt, the duration of the seasonal snowpack, and the date of snow removal.

3. *Forest disturbance simulations*

   Forest change is a function of forest practices, treeline migration, and increased forest disturbance as a result of drought, wildfire, disease and/or insect infestation. We chose to examine the effects of grey stage mountain pine beetle, moderately severe wildfire, and clearcut harvesting, as they represent the most likely disturbances to affect this region, and are also the disturbances in which the working group was most interested. We addressed both elevation and forest cover change effects on snow accumulation and melt at the watershed scale, by dividing it into four hydrologic response units (HRU) of different mean elevation (Fig. A2).

In order to represent each of the disturbance scenarios within the model, model parameters were adjusted to values appropriate for each post-disturbance forest cover type (Table A1). The model was run for 2001-2002 and 2006-2007 as these years had the best fit between simulated and observed data in the baseline run, and thus best represent forest-snow interactions. They also represent a higher and a lower snow year, respectively, between which we would expect to see different responses to forest change. For each year, the model was run with successively greater disturbance across the watershed (e.g., all HRUs containing mature forest, then HRU 1 containing post-MPB forest and HRUs 2-4 containing mature forest, then HRUs 1-2 containing post-MPB forest and HRUs 3-4 containing mature forest, etc.). As with the climate sensitivity tests, we focused specifically on the timing and magnitude of peak snow accumulation, the timing and rate of snowmelt, the duration of the seasonal snowpack, and the date of snow removal.

4. *Effects on hydrology*

We used the modelling outputs in combination with process knowledge of snow accumulation, melt and runoff to examine the possible effects of climate and forest cover change on watershed runoff.

4.0 Collaboration

This project is strongly linked with ongoing water supply modelling and operational water management in the Okanagan Basin (Okanagan Basin Water Board), the long-term UPCr watershed experiment (EP956), and ongoing groundwater research at both UPCr and throughout the Okanagan Basin (D. Allen, SFU). It is also linked with FFESC projects relating to climate change (Spittlehouse et al., Project 14), and to the water-related objectives of the Forests and Range Evaluation Program (FREP) (BC Ministry of Forests and Range 2007). It is also linked with Project 01 (Bladon et al.), as it provides key information on post-disturbance hydrology and management implications. Finally, it is linked with Project 13 (Redding et al.) in that it utilizes key forest hydrology information contained in the Compendium of Forest Hydrology and Geomorphology in BC.

We collaborated with our working group (‘clients’) by maintaining regular contact with them regarding our project outcomes and making use of their contributions to our project. We also collaborated with other universities (University of Saskatchewan) to get the model working in this watershed. We collaborated with our consultants (G2O Services, Watersmith Research, Rowan Systems, Zimonick Enterprises, Skyline Forestry) to ensure the highest possible standards of data collection and that climate sensitivity data analysis was expedited.

5.0 Communication

All participants in this project communicated routinely throughout the project as our research approach evolved, to resolve technical issues, assess model output, interpret results and plan next steps. We held three working group meetings throughout the course of the project. The first was in Kelowna in November 2010, and many of the working group members were able to attend. We outlined the project goals and approach, and invited comments and discussion regarding the potential applicability of the project to the work of each individual working group member. The second meeting was via conference call in February 2011, and focused on progress to date including some of the difficulties in setting up and running the model, as well as evolution of the project plan. Working group members provided feedback on the progress to date and outlined additional areas where they felt we could provide useful information. The final meeting was held via conference call in January 2012, and outlined the project outcomes and implications for water supply in the Okanagan region. The working group found the results highly useful for their purposes, and also provided additional topics that they hoped we would be able to pursue in the future. There was considerable interest from the group in moving forward with this modelling work to address additional questions around forest regeneration and hydrologic recovery, as well as contributions of snowmelt to groundwater recharge.

Since the interim report, we have presented (and plan to present) this work at the following scientific meetings:

(1) Boon S, Davis R, Winkler RD, Pomeroy J, Spittlehouse D. 2012. Simulating the effects of pine beetle and wildfire on snow accumulation and melt in the Okanagan region. *Canadian Geophysical Union-Canadian Water Resources Association Joint Annual Meeting.* Banff: 5-8 June.

(2) Winkler RD, Boon S, Spittlehouse D. 2012. Snow and streamflow response to logging at Upper Penticton Creek. *Canadian Geophysical Union-Canadian Water Resources Association Joint Annual Meeting*. Banff: 5-8 June.

(3) Boon S, Davis R, Winkler RD, Pomeroy J, Spittlehouse D. 2012. Hydrologic response to climate change related forest disturbance in the Okanagan. *SISCO Winter Workshop – Management Strategies for Post Mountain Pine Beetle Forests.* Salmon Arm: 4-5 April.

(4) Winkler RD, Boon S, Redding T. 2012. Forest watershed science in the southern Interior. *Western Division – Canadian Association of Geographers Annual Meeting.* Kelowna: 8-10 Mar.

(5) Boon S. 2012. Cold regions ecohydrology in Canada's mountain regions. *Oregon State University, HJ Andrews Long Term Ecological Research Program Brown Bag series.* Corvallis: 8 Feb.

(6) Winkler RD, Boon S, Davis R, Spittlehouse D. 2011. The effects of forest cover and climate change on snowmelt dominated water supplies in the Okanagan. *SISCO Winter Workshop –*

Forest Stewardship in the Context of the Forest & Range Practices Act and Professional Reliance: Moving Forward with New Dynamics and New Directions. Naramata: 4-6 Apr.

(7) Davis R, Boon S, Pomeroy JW, Winkler R. 2011. Modeling snowmelt runoff response to wildfire in the Okanagan basin, British Columbia, Canada. *68th Annual Meeting of the Eastern Snow Conference.* Montreal: 14-16 Jun.

(8) Davis R, Boon S, Winkler R, Pomeroy JW. 2011. Modeling snowmelt runoff response to forest disturbance in the Okanagan basin, British Columbia, Canada. *Canadian Geophysical Union Annual Meeting.* Banff: 15-18 May.

We are planning a public lecture at Okanagan College (Penticton campus) for spring 2012, which will be organized by a working group member (Todd Redding, previously of FORREX and now with the College). Rita Winkler is hosting the annual Provincial Hydrologists' tour in the Okanagan during the first week of July, where we will discuss our study results. Additionally, we are planning a short paper in Streamline Watershed Management Bulletin to summarize results for operational users. We are also developing a manuscript (Modelled snowcover response to forest disturbance in the Okanagan region, British Columbia) for submission to Hydrology and Earth System Science that will outline results for a scientific audience.

6.0 Research outcomes

1. Baseline run

Each year is labeled according to the spring snow period (e.g. Oct 2000-Jul 2001 = 2001). The model did a good job of simulating snow water equivalent (SWE) in both the clearcut and the mature forest, although the former had a better model fit (Fig. A3). The model oversimulated in both sites in 2000 and 2001, and undersimulated in both sites in 2006 and 2008. However, the overall model fit statistics indicated good fit between simulated and measured values (Table A2). We therefore selected years with best fit between the modeled and measured data for the climate sensitivity tests (2003) and forest disturbance scenarios (2002 and 2007). While the model was run for all four HRUs, we focused on the lowest (HRU1) and highest elevation (HRU4) units as they show the greatest differences in response. HRU2 responded similarly to HRU1, and HRU3 responded similarly to HRU4.

2. Climate sensitivity

Snow sensitivity to climate change was modeled for two forest cover extremes: mature forest (MF) and clearcut (CC). They represent forest cover end-members against which to compare the effects of natural disturbance.

In MF, increasing air temperature reduced the length of time that SWE remained at a maximum (Fig. A4), and shifted the complete removal of the snowpack to earlier in the spring. This change was greatest at lower elevations in response to small changes in air temperature. However, with continued air temperature increases, peak SWE at higher elevations became increasingly sensitive. Even with the highest air temperature increase, however, MF was able to retain a winter snowpack whereas in CC, the midwinter snowpack was periodically reduced to zero. In CC, the date of peak SWE stayed relatively constant with increasing air temperature (Fig. A4), but the total amount of SWE declined and the snowpack was removed more quickly.

Increasing winter precipitation caused stepwise increases in SWE in both MF and CC (Fig. A5), with minimal differences between elevations and between the two cover types due to a fairly uniform SWE distribution across the watershed.

Increasing both air temperature and precipitation showed that seasonal SWE evolution was dominated by the temperature signal: increased precipitation did not offset increased air temperature (Fig. A6). As temperatures increased, the duration of peak SWE in MF decreased. In CC, the total SWE accumulation decreased likely as a result of an increase in the proportion of precipitation falling as rain rather than snow. In MF, the lower elevations were more sensitive to change than the upper elevations: SWE at low elevations changed noticeably with only a 1ºC/5% increase in temperature and precipitation combined. At high elevation, however, a change of 2ºC/10% was required before seasonal SWE was affected, and there was minimal difference between the final two temp/precip scenarios. With a mature forest cover (MF), the higher elevations experienced the majority of SWE change in the ablation period, while lower elevations saw SWE change in both the accumulation and ablation periods. In contrast, with a clearcut (CC) cover all elevations were affected in both the accumulation and ablation periods, although total SWE was greater overall at higher elevations.

In both MF and CC, increasing air temperature resulted in a decline in maximum SWE at all elevations (Fig. A7). However, the effect of elevation was greater in CC than MF, where the higher elevations retained more SWE even as air temperature increased. Increasing precipitation resulted in a linear increase in maximum SWE in both MF and CC; again elevation was more significant in CC. Finally, the combined increase in air temperature and precipitation showed that maximum SWE at lower elevations were most sensitive in MF, whereas maximum SWE at all elevations was sensitive in CC.

Increasing air temperature also reduced the snow season duration. In MF, snow duration decreased from 180 days under normal conditions, to <60 days with a maximum 4ºC temperature increase (Fig. A8). The effect was even more pronounced in CC, where the snow duration dropped to 0 days at the lower elevations with a 2.5ºC temperature increase, and reached 0 days at all elevations once temperature increased by 3.5ºC. Increasing precipitation had a minimal effect on snow duration: MF responded similarly at all elevations, while CC had a shorter season at low elevations and longer at higher elevations. Increasing both temperature and precipitation, however, initially resulted in a slightly longer snow duration in MF as noted in the previous section. However, with increasing air temperature more precipitation fell as rain thus the snow duration declined. Again in CC, the highest elevations retained snow cover until the greatest T/P increases, before snow duration dropped to zero.

3. Snow response to climate change related forest disturbance

Two disturbance scenarios were selected as most likely to occur due to climate warming: defoliation as a result of insect-related tree mortality (in this case mountain pine beetle; MPB), and wildfire (WF). Forest disturbance scenarios were applied to the 2002 (lower snow year) and 2007 (higher snow year) datasets, given that the role of the forest canopy in ground snow accumulation varies with snowfall timing and magnitude. Disturbance outputs were compared with the end-members described above: mature forest (MF) and clearcut (CC). While the model was run for all four HRUs, we focus mainly on the lowest (HRU1) and highest elevation (HRU4) ones as they show the greatest differences in response.

(a) MPB

Snow processes after MPB behaved most similarly to those in MF. After MPB attack in the low snow year, peak SWE declined at low elevations and melt occurred slightly earlier, while at high elevations there was no change in peak SWE, but melt occurred more rapidly and the snowpack was removed more quickly (Figs. A9-A11). Differences in snow season duration became more variable between lower and higher elevations following MPB (Fig. A12), while snow duration in the two low elevation HRUs became more similar.

In the high snow year following MPB attack, there was no change in the amount of peak SWE at either low or high elevations (Figs. A9-A11). However, at both elevations melt occurred more rapidly and the snowpack was removed more quickly. Thus the duration of snow cover decreased, as did the variation in snow cover duration between elevations (Fig. A12). Additionally, the post-MPB melt rate was less variable across elevations in the high than the low snow year, likely due to the greater spatial variability of snow accumulation in the low snow year (Fig. A11).

(b) Wildfire

Snow processes after wildfire (WF) behaved differently than those after MPB and similarly to those following clearcutting. In both the low and high snow years, WF resulted in increased peak SWE and more rapid melt at all elevations, with earlier snowpack removal (Figs. A9-A11). However, there was a greater increase in peak SWE in the high snow year, and melt rates and snow duration differed between years (Fig. A11-A12). In the low snow year, the melt rate was highest in WF out of all the forest cover/disturbance types, and was the same at all elevations. Additionally, snow duration declined substantially when shifting from MPB to WF disturbance, and became similar across elevations. When CC was applied, however, the snow duration increased slightly as a result of larger accumulations of snow. In the high snow year (2007), the melt rate in MF was lower at lower elevations, and the most variable between elevations of all the disturbance/forest cover types.

7.0 Conclusions

The key findings of this project suggest that in headwater basins on the Okanagan Plateau, snow accumulation and ablation will respond to increasing air temperature and precipitation associated with climate change. While the specific nature of snowpack response will vary with watershed characteristics, the direction of response will be similar across Okanagan headwater basins. Application of the CRHModel at Upper Penticton Creek suggests that increasing air temperature and precipitation will result in the following:

- a decrease in maximum snow accumulation (SWE) and shorter snow season at high elevations
- greater reductions in both maximum SWE and snowpack duration in response to smaller temperature increases at low than high elevations in headwater catchments
- a greater proportion of precipitation falling as rain
- an increase in mid-winter melt events, particularly in clearcuts
- greater snow sensitivity to climate change in clearcuts than mature forests
- similar snow sensitivity to climate change in stands killed by MPB to that in mature green forests, while those in moderately severe burns will respond similar to clearcuts
- a decrease in SWE at low elevations in headwater basins, and a reduction in snow duration at high elevations, suggesting earlier and more rapid increases in streamflow in spring, as well as an earlier return to baseflow.

These results have implications for both forest and water management including:

- reduced high elevation over-winter water storage
- compressed snowmelt runoff seasons
- changes in winter wildlife habitat
- reductions in ski and snowmobile season duration
- more frequent occurrence of flashier high flow events in small headwater streams, and an associated potential increase in erosion risk
- increased stress on road drainage structures
- added complexity in management of water storage facilities
- earlier reductions in available moisture for tree growth, particularly at lower elevations
- potential risk of early season desiccation damage to trees no longer protected by snow
- longer growing seasons but with greater chance of late season drought stress
- earlier and longer low flow seasons
- increased frequency of low flows below minimums for aquatic habitat

8.0 Recommendations for future action

Climate related changes in the timing, magnitude and reliability of snow dominated runoff from upland catchments will affect both aquatic habitat and water supplies. Where change is extensive and of sufficient magnitude, ensuring that adequate flows are retained for aquatic life, agriculture, industry and domestic consumption will require adaptive forest and water management strategies. The modelling work completed at Upper Penticton Creek is a first step towards understanding how upland watersheds are likely to respond to climate and forest cover change. Although this project focuses on only two small upland basins and several selected disturbances, it provides a strong indication of the direction of expected change across Okanagan headwater basins, and points to the need for continuing research to confirm and expand upon these initial results. Reductions in and earlier delivery of snowmelt runoff will require adaptations in forest and aquatic resource management, water storage, delivery and allocation and in community development, to ensure continued security of water supplies. Actions that should be taken by government resource agencies, industry, water purveyors and municipalities to improve water management and use in the Okanagan in preparation for future climate- and forest-related changes in the hydrologic regime include:

- a critical review of water flows and licenses in the Okanagan Valley to ensure that streamflow is not currently over-allocated
- where streams are over-allocated, or approaching the limit required to protect aquatic habitat, no new water licenses should be issued until such time as a detailed watershed-specific evaluation of current and future water supply potential has been completed
- forest management should maintain diversity in stand composition and age classes across watersheds to vary snow accumulation and ablation rates, summer evaporative losses, and water uptake by forest cover, and to desynchronize runoff
- water storage and delivery infrastructure should be assessed to ensure sufficient capacity to withstand higher short-duration flows in spring, rapid response to summer storms and reduced late season flows. This will minimize the risk of breaching and flooding in spring, while maintaining a sufficient water supply for the prolonged low flow season
- manage water use, whether by agriculture, industry or communities, as a finite rather than an infinite resource
- consider future water supplies when approving expansion of communities throughout the Okanagan Valley
- continue to fund and support long-term hydrometric monitoring in the Okanagan Basin
- continue research into hydrologic processes on forest and agricultural land, and into climate change and water supply management, including innovations in water engineering, home appliances, landscaping, and irrigation.

9.0 Extension of research outcomes

Our results regarding the hydrologic function of grey stands post-MPB attack, in combination with field results from other study locations, are being incorporated into hydrologic assessments and source-to-tap assessments throughout the Okanagan. Results relating to changes in snowmelt-generated water supplies following climate change have been shared with the working group. From this, they have indicated their interest in – and willingness to be involved with – further work, including the combined effects of both extensive forest regrowth and climate change on water yield. Abstracts have been accepted for the results to be presented at scientific and technical conferences over the next six months, and a journal article is being prepared for the scientific community. Work is also underway to develop an operational summary of the results. Results will be shared with operational professionals, policy specialists and decision-makers through workshops, a technical extension article, a project summary on the UPCr website, and during forest development planning field reviews and other expert advice. However, as there is no mandated requirement for forest professionals to apply information provided by research other than through professional reliance, there is no guarantee of how they will apply the new knowledge gained through this project.

10.0 References

Alila Y, Luo Y. 2007. Delineating the limits of peak flow and water yield responses to clearcut salvage logging in large watersheds. In: T. Redding (Editor), *Proceedings of the Mountain Pine Beetle and Watershed Hydrology Workshop: Preliminary results of research from BC, Alberta and Colorado*. FORREX, Kelowna, BC.

Beckers J, Smerdon B, Wilson M. 2009. Review of hydrologic models for forest management and climate change applications in BC and Alberta. *FORREX Forum for Research and Extension in Natural Resources,* Kamloops, BC, FORREX Series 25. www.forrex.org/publications/forrexseries/fs25.pdf

Bethlalmy N. 1974. Water supply as affected by micro- and macro-watershed management decisions on forest lands. *Northwest Science* 48(1): 1-8.

Bewley D, Alila Y, Varhola A. 2010. Variability of snow water equivalent and snow energetics across a large catchment subject to mountain pine beetle infestation and rapid salvage logging. *Journal of Hydrology* 388: 464-479.

Boon S. 2009. Snow ablation energy balance in a dead forest stand. *Hydrological Processes* 23: 2600-2610.

British Columbia Ministry of Forests and Range. 2007. *Forests and Range Evaluation Program 5 Year Strategic Plan 2007-2011*. 8 pp. Available at:

http://www.for.gov.bc.ca/ftp/hfp/external/!publish/frep/library/FREP_strategy_v2_Oct22_08_unedited.pdf

Carver MW, Weiler M, Scheffler C, Rosin K. 2009. Development and application of a peak-flow hazard model for the Fraser basin (British Columbia). *Mountain Pine Beetle Working Paper 2009-13*. Natural Resources Canada, Canadian Forest Service: Pacific Forestry Centre: Victoria, BC. 35 pp.

Chang M. 2003. *Forest Hydrology: an Introduction to Water and Forests*. Boca Raton: CRC Press, 392 pp.

Cohen S, Neilsen D, Smith S, Neale T, Taylor B, Barton M, Merritt W, Alila Y, Shepherd P, McNeill R, Tansey J, Carmichael J, Langsdale S. 2006. Learning with local help: expanding the dialogue on climate change and water management in the Okanagan region, British Columbia, Canada. *Climatic Change* 75: 331-358.

Hibbert AR. 1967. Forest treatment effects on water yield. In: WE Sopper and HW Lull (Eds), *Forest Hydrology*. New York: Pergamon Press, p. 527-543.

Jones JA, Achterman GL, Augustine LA, Creed IF, Ffolliot PF, MacDonald L, Wemple BC. 2009. Hydrologic effects of a changing forested landscape - challenges for the hydrological sciences. *Hydrological Processes* 23: 2699–2704.

Littell JS, McKenzie D, Peterson DL, Westerling AL. 2009. Climate and wildfire area burned in western US ecoprovinces, 1916-2003. *Ecological Applications* 19(4): 1003-1021.

Okanagan Water Stewardship Council. 2008. Okanagan sustainable water strategy. Action Plan 1.0. *Okanagan Basin Water Board*, 124 pp.

Pomeroy JW, Gray DM, Hedstrom NR, Janowicz JR. 2002. Prediction of seasonal snow accumulation in cold climate forests. *Hydrological Processes* 16: 3543-3558.

Pomeroy JW, Gray DM, Brown T, Hedstrom NH, Quinton WL, Granger RJ, Carey SK. 2007. The Cold Regions Hydrological Model: a platform for basing process representation and model structure on physical evidence. *Hydrological Processes* 21: 2650-2667.

Pugh E, Small E. 2011. The impact of pine beetle infestation on snow accumulation and melt in the headwaters of the Colorado River. *Ecohydrology*, DOI: 10.1002/eco.239.

Rutter N, Essery R, Pomeroy JW, Altimir N, Andreadis K, Baker I, Barr A, Bartlett P, Boone A, Deng H, Douville H, Dutra E, Elder KJ, Ellis CR, Feng X, Gelfan A, Goodbody A, Gusev Y, Gustafsson D, Hellstrom R, Hirabayashi Y, Hirota T, Jonas T, Koren V, Kuragina A, Lettenmaier DP, Li W, Luce CH, Martin E, Nasonova O, Pumpanen J, Pyles RD, Samuelsson P, Sandells M, Schadler G, Shmakin A, Smirnova TG, Stahli M, Stockli R, Strasser U, Su H, Suzuki K, Takata K, Tanaka K, Thompson E, Vesala T, Viterbo P, Wiltshire A, Xia K, Xue Y, Yamazaki T. 2009. Evaluation of forest snow processes models (SnowMIP2). *Journal of Geophysical Research* 114. doi:10.1029/2008JD011063.

Schnorbus M. 2011. A synthesis of the hydrological consequences of large-scale mountain pine beetle disturbance. *Mountain Pine Beetle Working Paper 2010-01*. Natural Resources Canada, Canadian Forest Service: Pacific Forestry Centre: Victoria, BC. 30 pp.

Seibert J, McDonnell JJ, Woodsmith RD. 2010. Effects of wildfire on catchment runoff response: a modelling approach to detect changes in snow-dominated forested catchments. *Hydrology Research* 41(5): 378-390.

Seidl R, Fernandes PM, Fonseca TF, Gillet F, Jonsson AM, Merganicova K, Netherer S, Arpaci A, Bontemps JD, Bugmann H, Gonzalez-Olabarria JR, Lasch PM, Meredieu C, Moreira F, Schelhaas MJ, Mohren F. 2010. Modelling natural disturbances in forest ecosystems: a review. *Ecological Modelling* 222(4): 903-924.

van de Vosse H. 2008. Mountain Pine Beetle Infestation: Hydrological Impacts. *Ministry of Environment Mountain Pine Beetle Action Team:* Prince George, BC.

Westerling AL, Hidalgo HG, Cayan DR, Swetnam TW. 2006. Warming and earlier spring increase western U.S. forest wildfire activity. *Science* 313(5789): 940-943.

Wigmosta MS, Burges SJ (Eds). 2001. Land use and watersheds: human influence on hydrology and geomorphology in urban and forest areas. *Water Science Applications Vol. 2*, 228 pp., AGU, Washington, DC.

Winkler RD, Spittlehouse DL, Golding DL. 2005. Measured differences in snow accumulation and melt among clearcut, juvenile, and mature forests in Southern British Columbia. *Hydrological Processes* 19:51-62.

Winkler R, Spittlehouse D, Allen D, Redding T, Giles T, Hope G, Heise B, Alila Y, Voeckler H. 2008. The Upper Penticton Creek Watershed Experiment: Integrated Water Resource Research on the Okanagan Plateau. *CWRA/OBWB: One Watershed - One Water* Conference Proceedings (21-23 Oct). p. 38-47.

Winkler RD, Boon S. 2009. A summary of research into the effects of mountain pine beetle related stand mortality on snow accumulation and ablation in BC. *Proceedings of the 77th Annual Meeting of the Western Snow Conference*. Canmore: April 20-23.

Ziemer RR, Lewis J, Rice RM, Lisle TE. 1991. Modeling the cumulative watershed effects of forest management strategies. *Journal of Environmental Quality* 20: 36-42.

APPENDIX I
TABLES AND FIGURES

Table A1. Selected parameter values used to represent varying forest cover types in the CRHModel. Values were derived from both field data and the published literature.

Parameter	Mature Forest	Mountain Pine Beetle	Wildfire	Clearcut
Tree Height (m)	17.8	17.0	15	0.25
Leaf Area Index	2.5	1.8	0.4	n/a
Sbar* (kg m^{-2})	6.6	5.8	2	n/a
Albedo decay rate of cold snow (s)	9×10^5	9×10^6	9×10^6	1×10^8
Albedo decay rate of warm snow (s)	1×10^3	1×10^4	1×10^4	1×10^6
Maximum snow albedo	0.84	0.80	0.63	0.84
Minimum snow albedo	0.36	0.35	0.50	0.72

**Maximum weight of intercepted snow.*

Table A2. Annual model fit statistics for the simulated years (2002, 2003, 2007) in the clearcut (CC) and mature forest (MF) model runs. RMSE = root mean squared error, r^2 = coefficient of variation.

	RMSE	Model Bias	Model Error	Nash-Sutcliffe	r^2	Equation of line
CC						
2002	42.07	-0.09	16.44	0.84	0.91	y = 1.12x - 37.77
2003	42.67	0.26	-34.63	0.84	0.94	y = 0.96x + 40.04
2007	40.58	-0.17	32.35	0.87	0.95	y = 1.01x - 34.32
MF						
2002	52.21	0.11	-24.32	0.49	0.89	y = 0.38x + 165.16
2003	107.65	0.56	-99.86	0.26	0.64	y = 0.25x + 234.00
2007	51.72	0.13	-24.83	0.53	0.89	y = 0.423x + 137.42

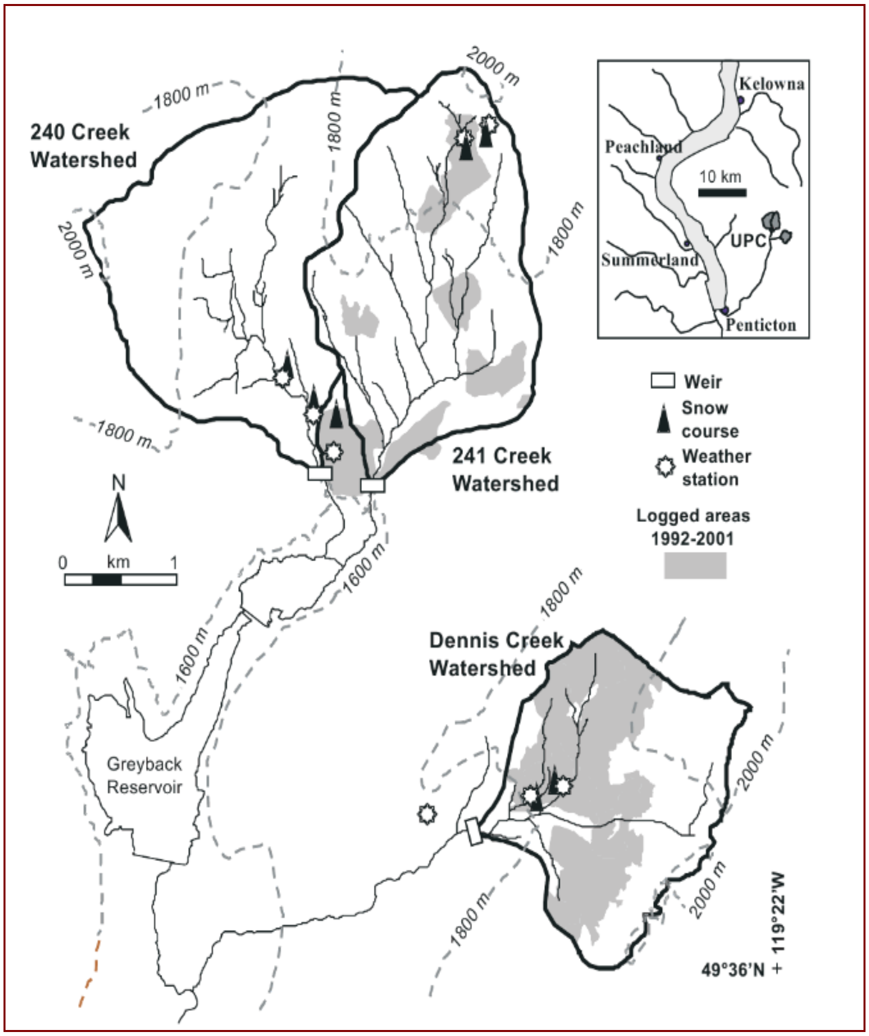


Figure A1. Stream network, monitoring stations, and harvested regions in the Upper Penticton Ck watershed; including 240 Creek, 241 Creek and Dennis Ck watersheds. This study focuses on 241 Ck Watershed.

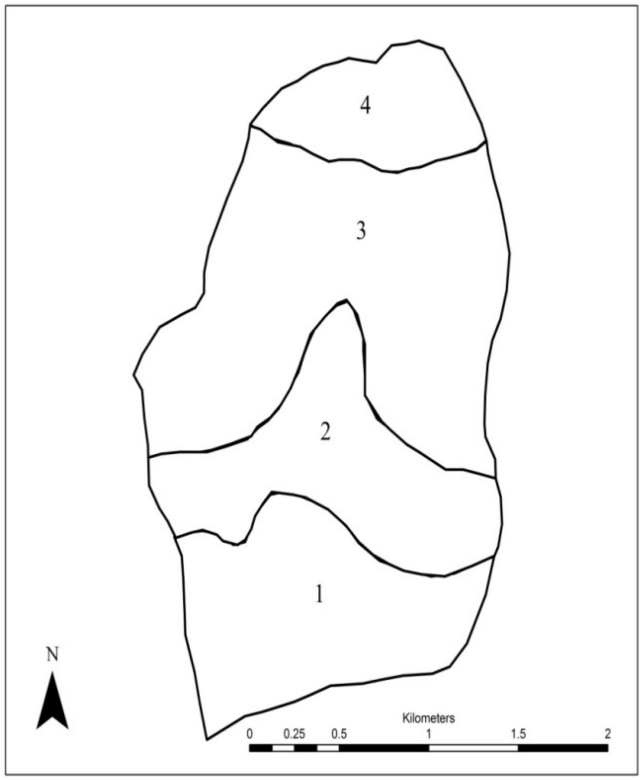


Figure A2. Hydrologic response units (HRUs) in the 241 Creek watershed based on elevation. Vegetation cover, slope and aspect are relatively uniform across the watershed.

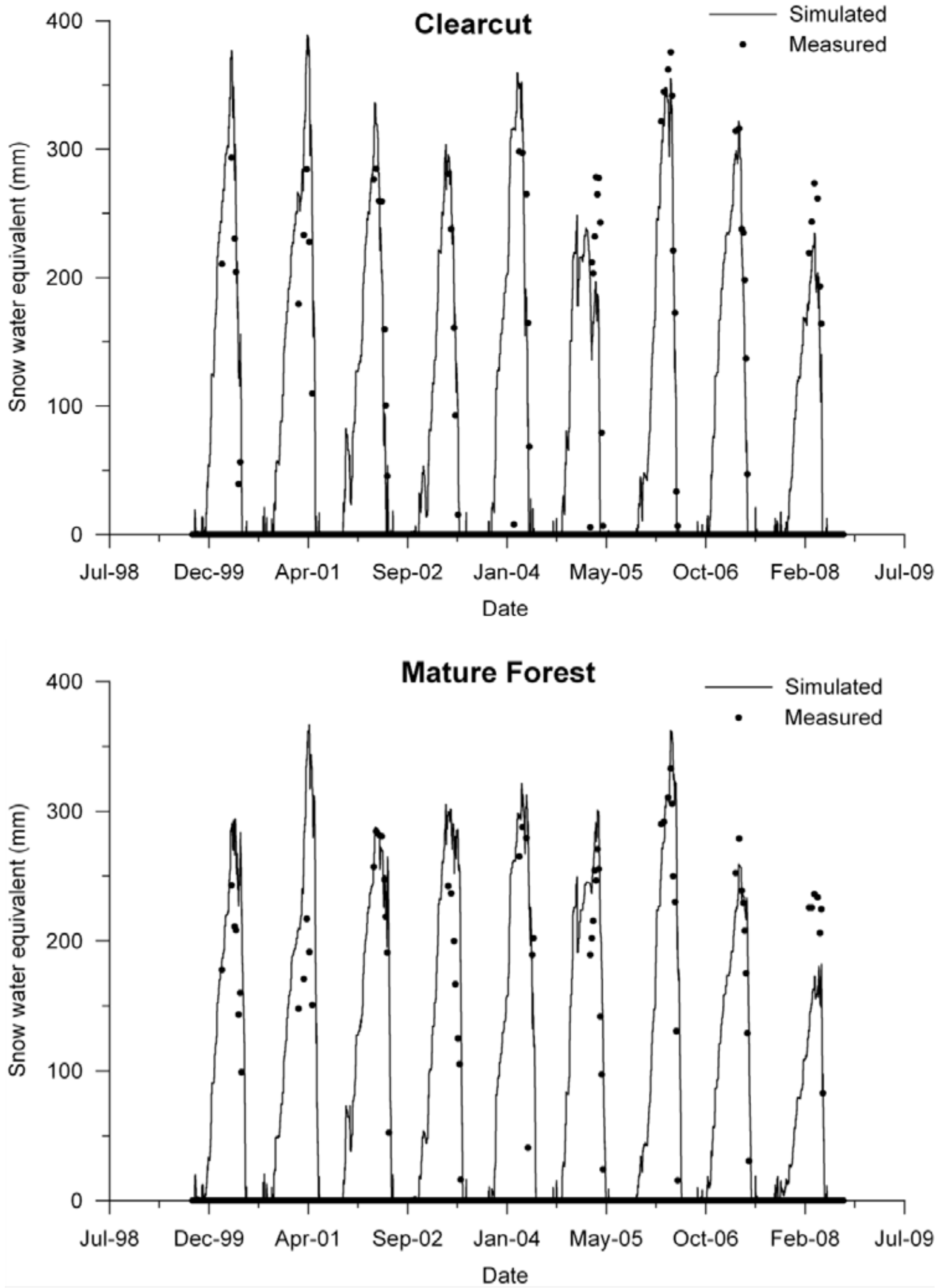


Figure A3. Simulated SWE (lines) and measured SWE (points) for the baseline runs, completed for each of a clearcut and a mature forest from October 1999 – July 2008.

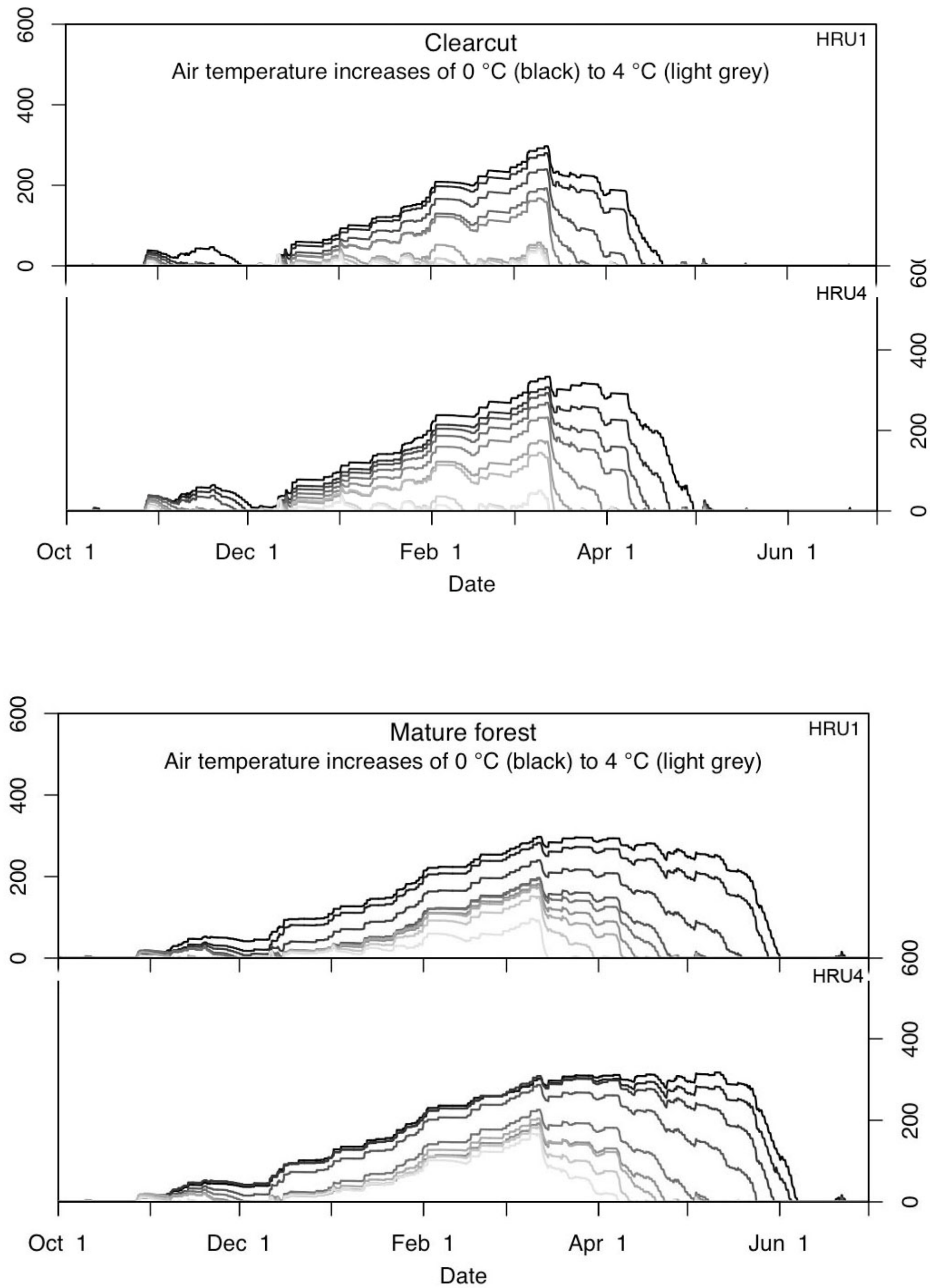


Figure A4. Sensitivity of seasonal snow water equivalent (SWE) to iterative increases in winter air temperature (from 0ºC to 4ºCby 0.5ºC increments), in both a clearcut and a mature forest. Note that this model test was conducted using data from 2002. Results are for the lowest (HRU1) and highest (HRU4) elevation HRUs, as they show the greatest difference in response.

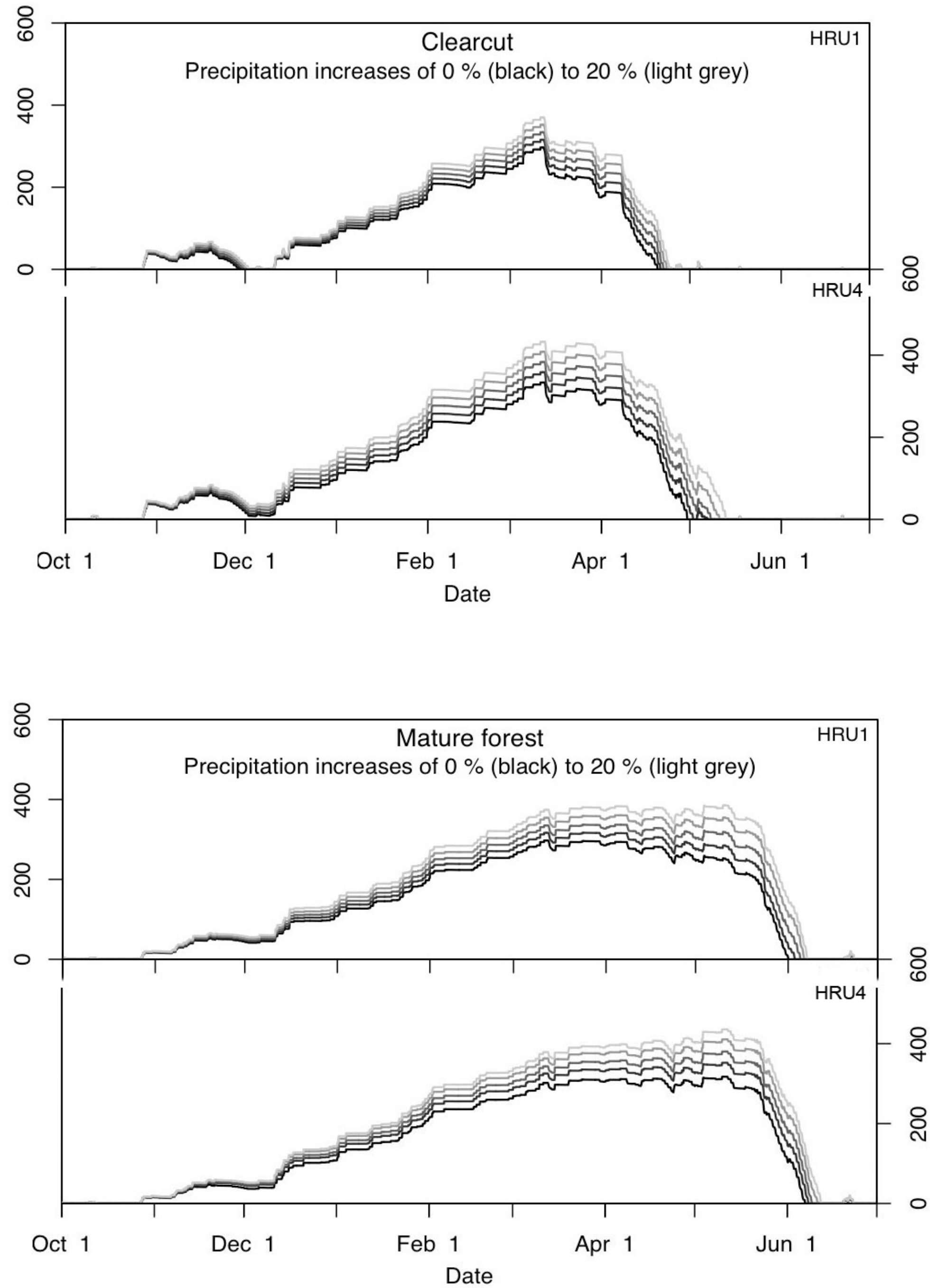
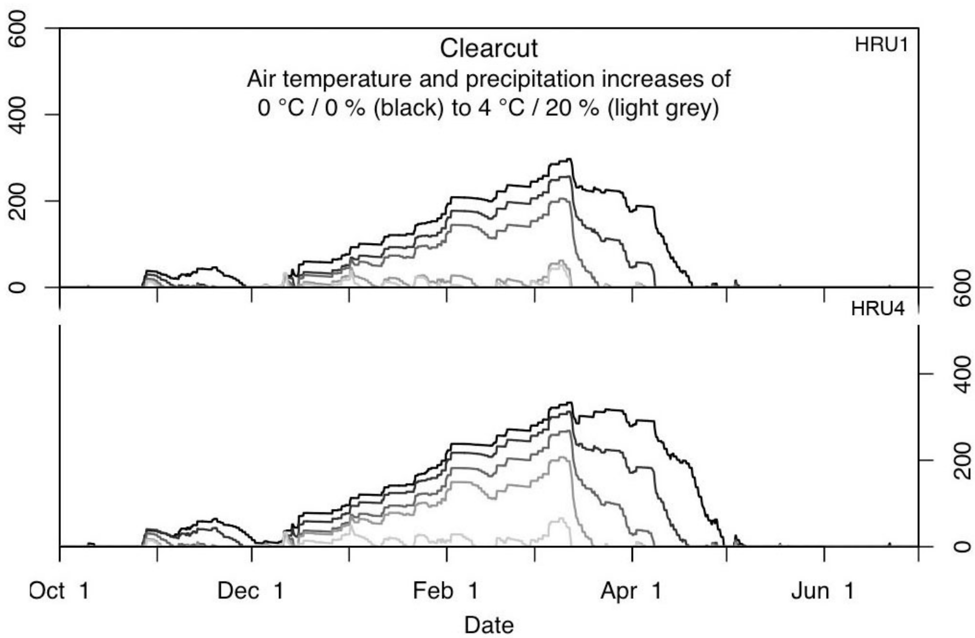


Figure A5. Sensitivity of seasonal snow water equivalent (SWE) to iterative increases in winter precipitation (from 0% to 20% by 5% increments), in both a clearcut and a mature forest stand. Note that this model test was conducted using data from 2002. Results are for the lowest (HRU1) and highest (HRU4) elevation HRUs, as they show the greatest difference in response.



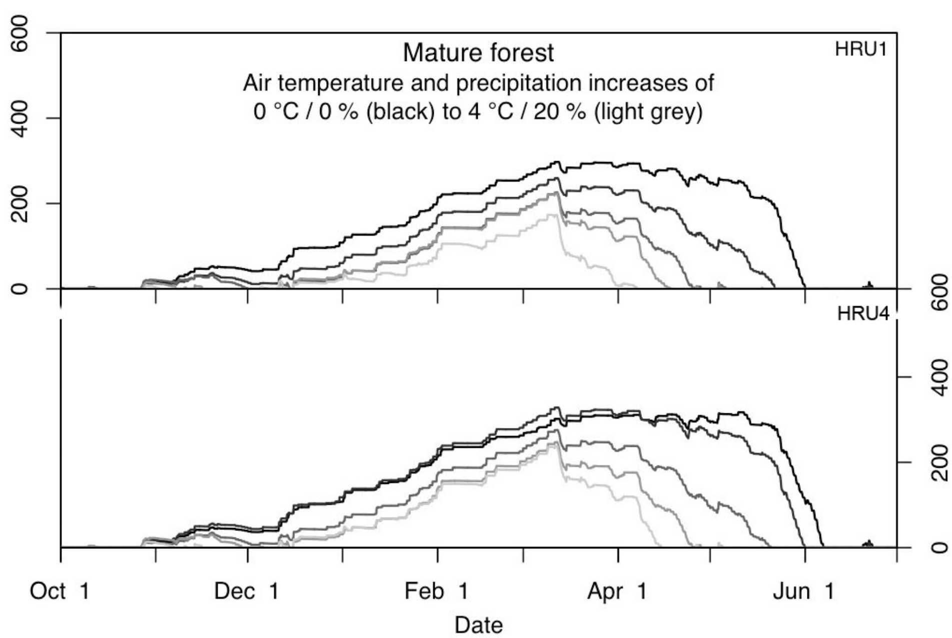


Figure A6. Sensitivity of seasonal snow water equivalent (SWE) to iterative increases in both winter air temperature (from 0ºC to 4ºC by 1ºC increments) and winter precipitation (from 0% to 20% by 5% increments), in both a clearcut and a mature forest stand. Note that this model test was conducted using data from 2002. Results are for the lowest (HRU1) and highest (HRU4) elevation HRUs, as they show the greatest difference in response.

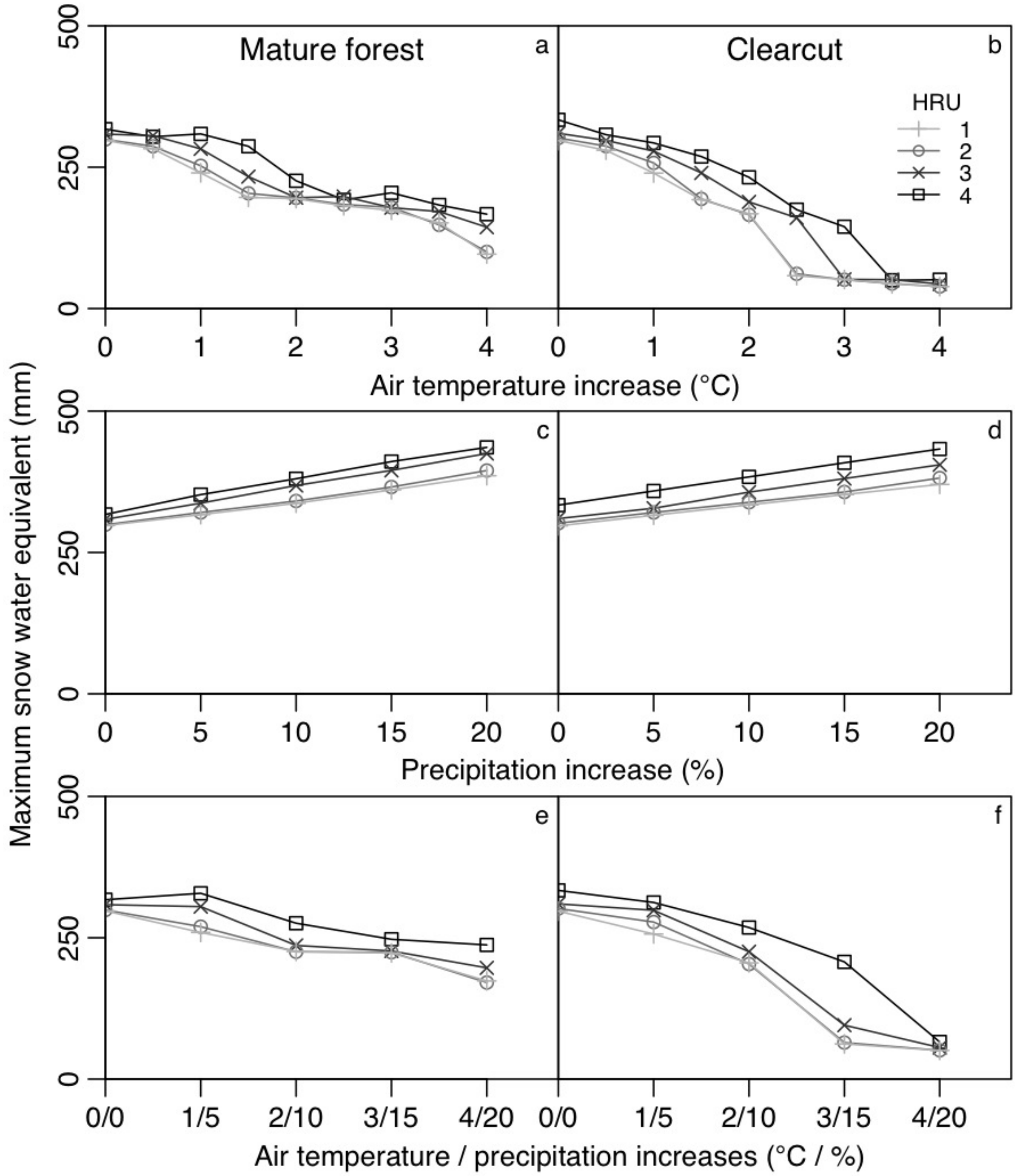


Figure A7. Change in seasonal maximum snow water equivalent (SWE in mm) for: (a) air temperature increases in the mature forest; (b) air temperature increases in the clearcut; (c) precipitation increases in the mature forest; (d) precipitation increases in the clearcut; (e) combined air temperature and precipitation increases in the mature forest; and, (f) combined air temperature and precipitation increases in the clearcut. Each line indicates the response for a different HRU (see legend).

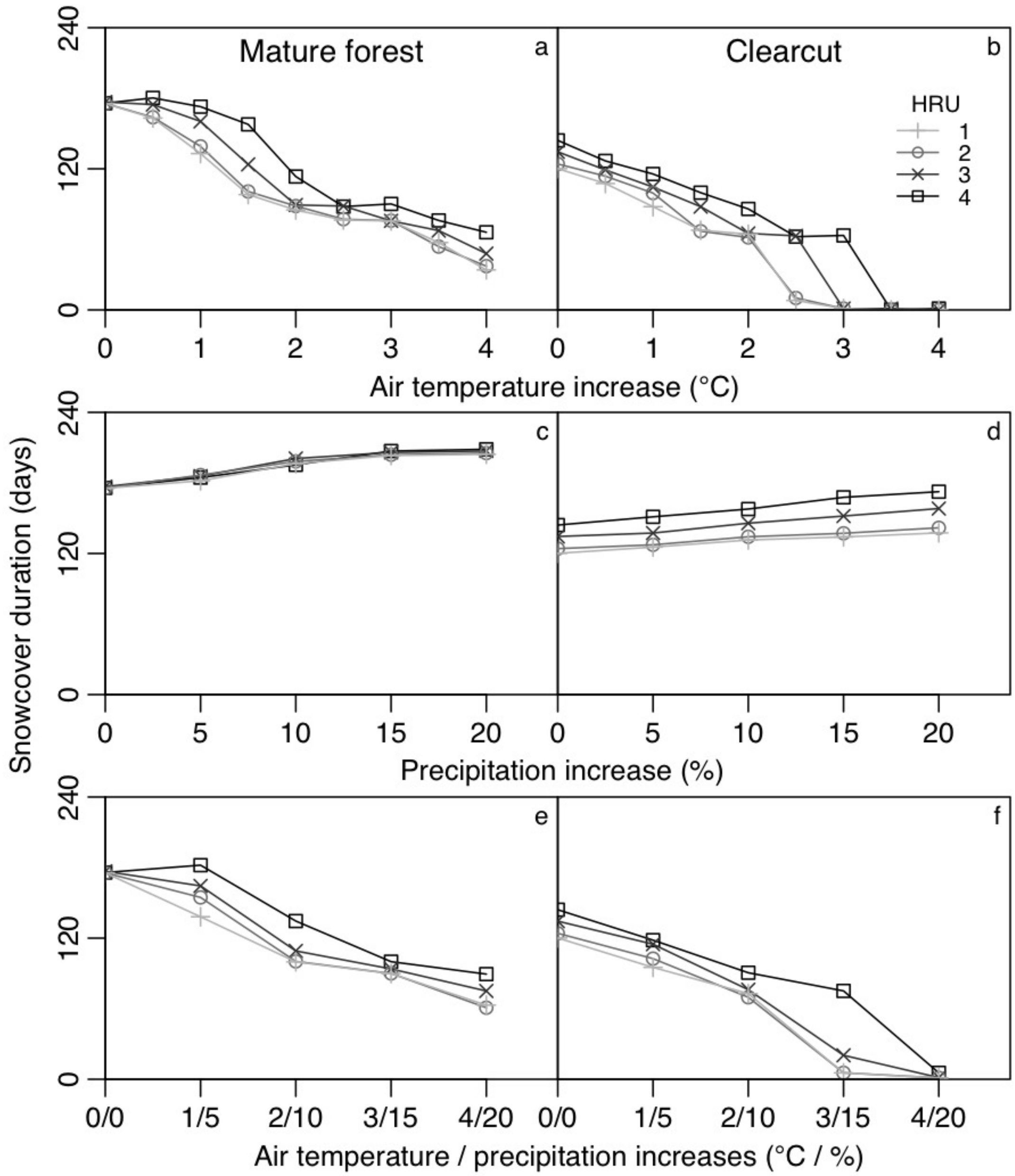
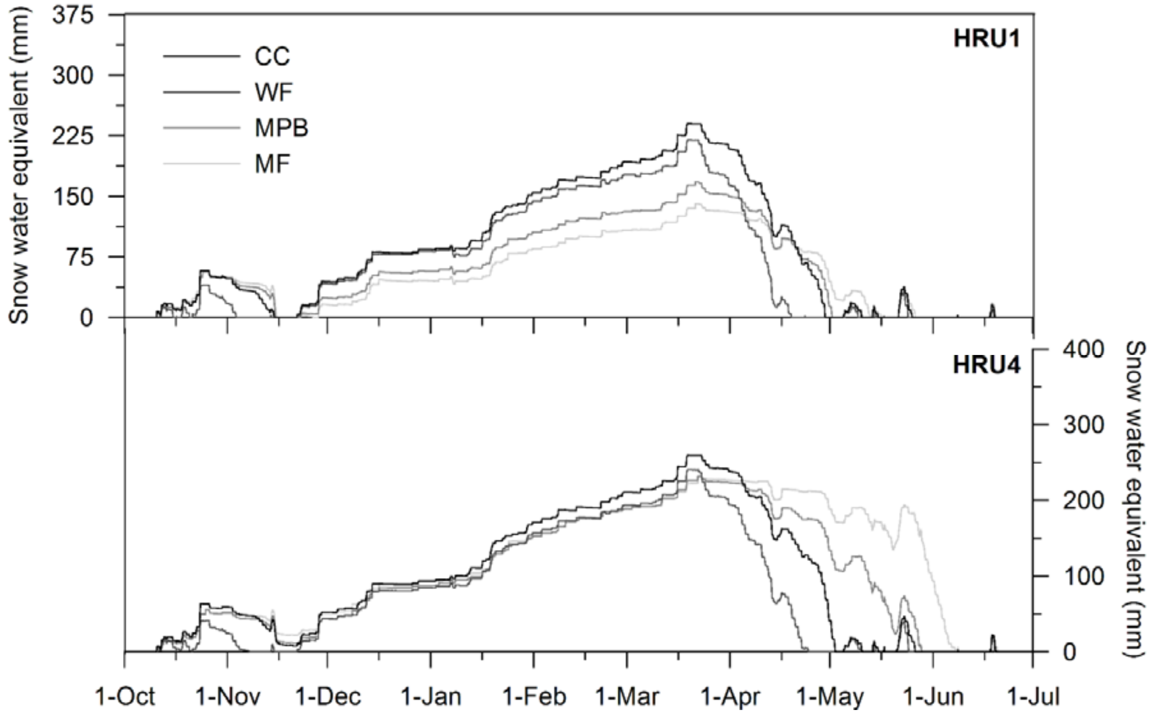
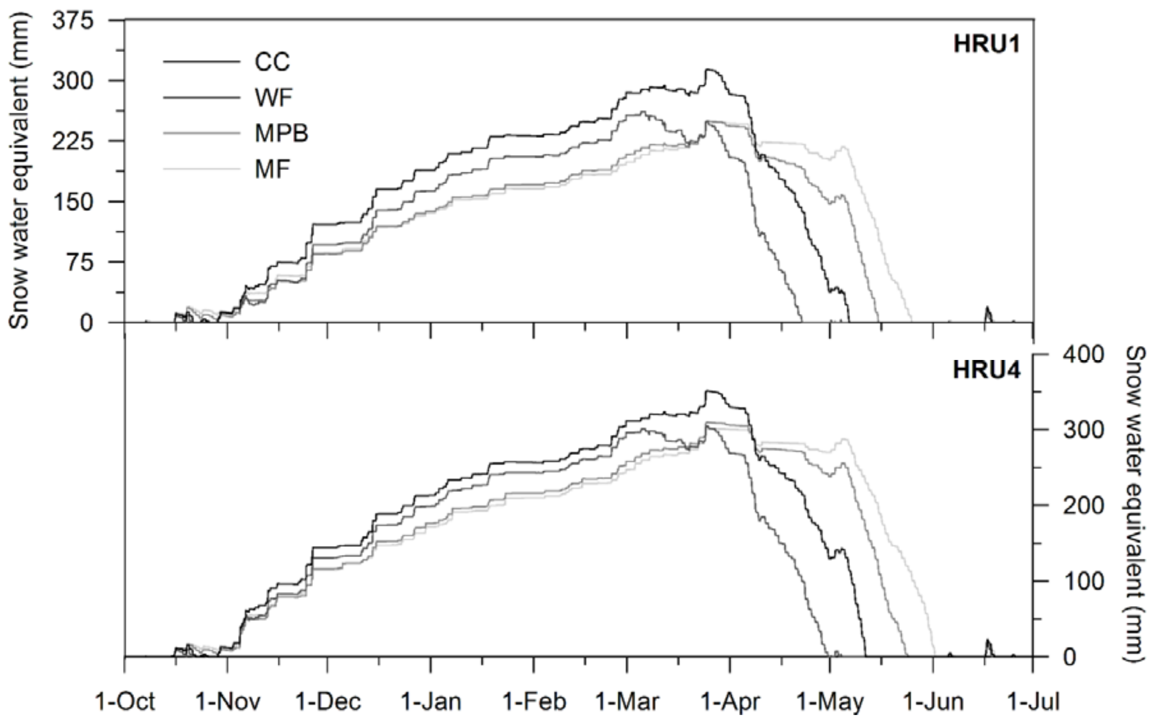


Figure A8. Change in snowcover duration (i.e., length of the snow season) in days for: (a) air temperature increases in the mature forest; (b) air temperature increases in the clearcut; (c) precipitation increases in the mature forest; (d) precipitation increases in the clearcut; (e) combined air temperature and precipitation increases in the mature forest; and, (f) combined air temperature and precipitation increases in the clearcut. Each line indicates the response for a different HRU (see legend).

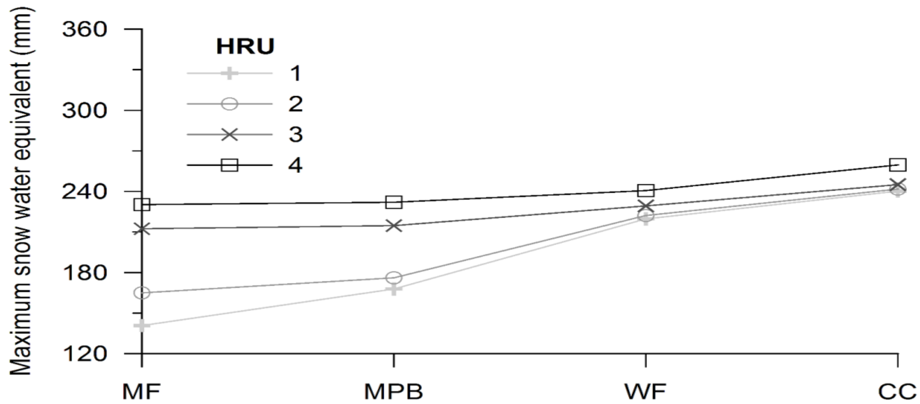


2002

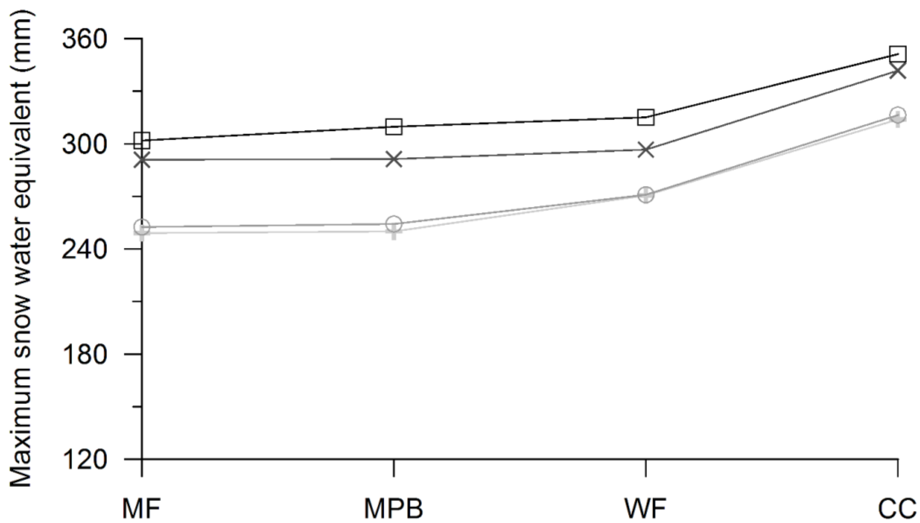


2007

Figure A9. Seasonal snowpack evolution in the lowest (HRU1) and highest (HRU4) elevation regions of the watershed for each forest cover scenario in 2002 (top) and 2007 (bottom). CC = clearcut, WF = wildfire, MPB = mountain pine beetle, MF = mature forest.

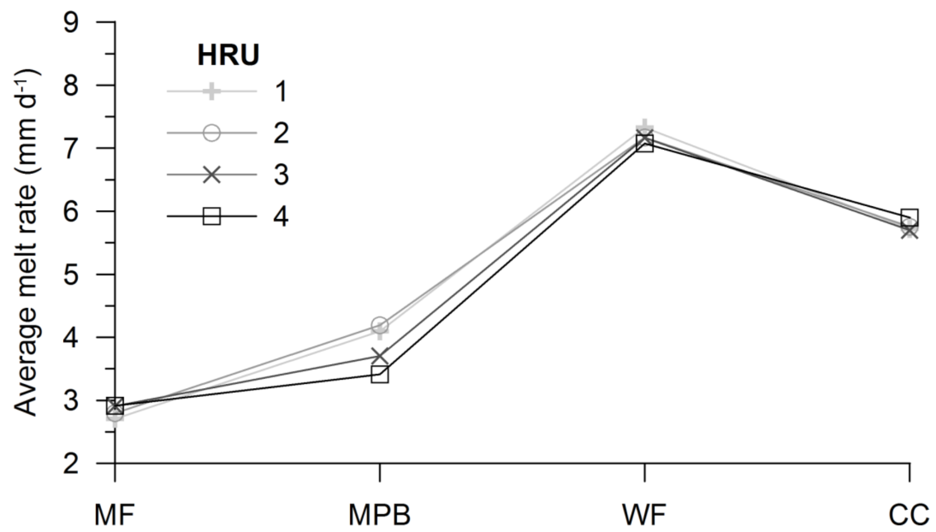


2002

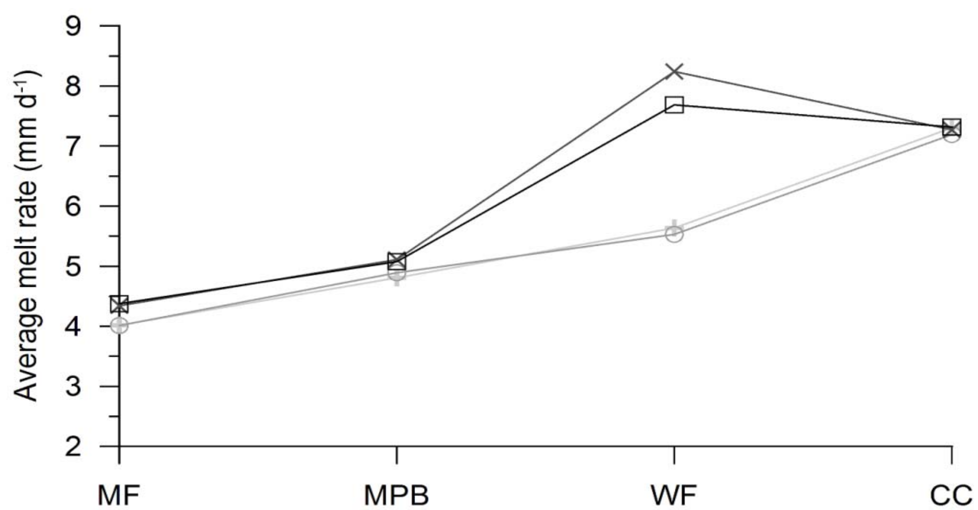


2007

Figure A10. Maximum snow water equivalent (SWE in mm) in each hydrologic response unit (HRU) under each disturbance scenario in 2002 (top) and 2007 (bottom). CC = clearcut, WF = wildfire, MPB = mountain pine beetle, MF = mature forest.

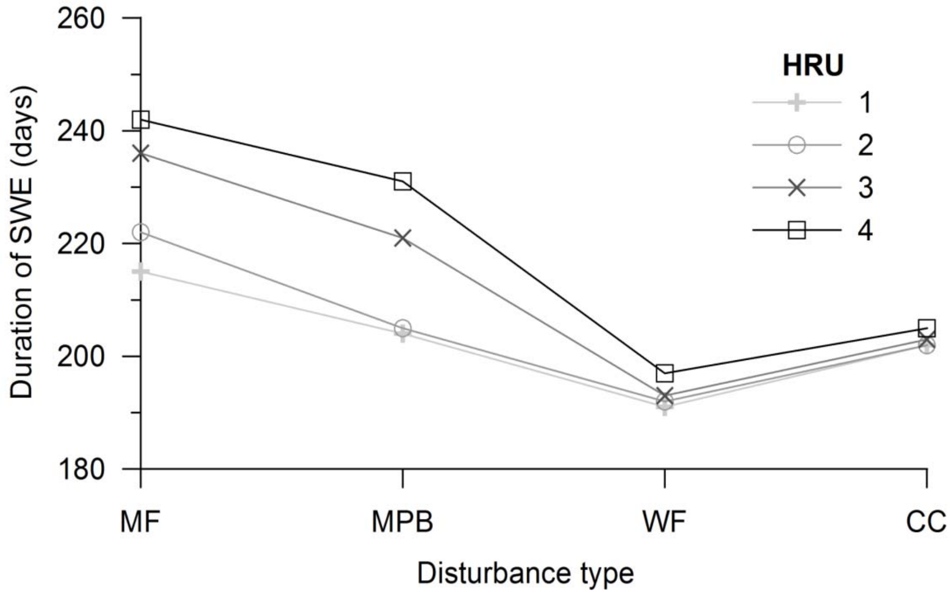


2002

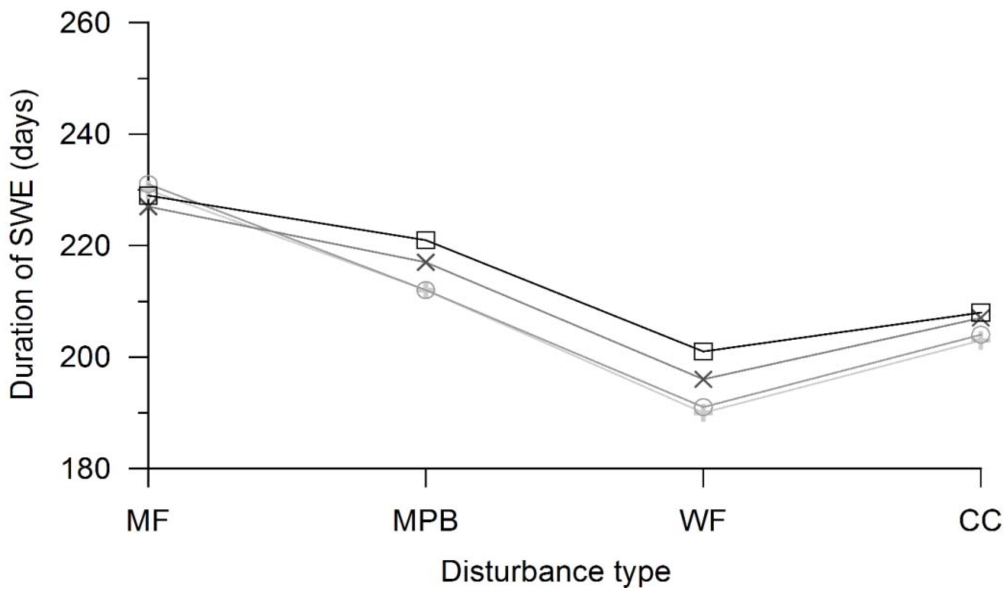


2007

Figure A11. Average melt rate (mm per day) in each hydrologic response unit (HRU) under each disturbance scenario in 2002 (top) and 2007 (bottom). CC = clearcut, WF = wildfire, MPB = mountain pine beetle, MF = mature forest.



2002



2007

Figure A12. Duration of SWE (in days) in each hydrologic response unit (HRU) under each disturbance scenario in 2002 (top) and 2007 (bottom). CC = clearcut, WF = wildfire, MPB = mountain pine beetle, MF = mature forest.

APPENDIX II

SCIENTIFIC METHODOLOGY

1.0 Field Data

Weather data were collected at the lower station at 241Cr (Fig. A1), using a Campbell Scientific CR1000 datalogger and the instruments listed in Table A2.1. Average hourly data was recorded from 60 s measurements of incoming solar radiation, air temperature, relative humidity, wind speed and precipitation (Table A2.2).

Table A2.1. Weather instruments and measurement height.

Variable	*Instrument model*	*Instrument accuracy*	*Height above ground (m)*
Incoming solar radiation	LiCor LI200 pyranometer	± 5%	3
Air temperature, relative humidity	Campbell Scientific HMP35C; in multi-plate radiation shield	± 0.4 °C, ± 3%	2.5
Wind speed	MetOne 013 wind speed sensor	± 2%	4
Precipitation (rain)	Texas Electronic TR525i tipping bucket	± 1%	0.5
Snow depth	Campbell Scientific UDG01 ultrasonic depth gauge	± 1 cm	2

Annual snow survey data have been collected at 241Cr since 1999 in two forested and clearcut site pairs (dots in Fig. A1). 32-point snow surveys grids were measured weekly or bi-weekly from February/early March until late May/early June, depending on snow accumulation conditions and funding availability. Snow water equivalent (SWE) was measured using the Standard Federal snow sampler weighed on a spring scale that provides direct values of SWE (Goodison et al. 1981). The following values were calculated annually from the field dataset: April 1 SWE, timing and magnitude of maximum SWE, date of 0 SWE, average melt rate, date of melt onset and SWE at melt onset, and maximum daily melt rate. Average melt rate was calculated as the average SWE lost per day between peak SWE and snow disappearance. Maximum daily melt rate was defined as the maximum daily SWE loss between peak SWE and snow removal.

2.0 Cold Regions Hydrological Model (CRHM)

CRHM is a physically based, semi-distributed modular software platform for building hydrological models written in C++ that uses a Microsoft Windows interface. A process module library links to physical data inputs to simulate basin hydrology. Each module employs a range of empirical, analytical and process-based algorithms and associated parameters and state variables to simulate hydrologic response for each hydrologic response unit (HRU). The user is able to select modules and algorithms based on the available input data. CRHM can also process interactions between HRUs to simulate intra-basin hydrological processes, and can be run with minimal calibration (Pomeroy et al. 2007).

CRHM can represent most hydrologic processes in a watershed that are critical for forest disturbance simulation, as it has been observed to be one of the better models for simulating forest management scenarios that require forest canopy manipulation, and is also able to represent snow processes well in forested and clearcut environments (Beckers et al. 2009; Rutter et al. 2009).

While CRHM has largely been applied outside of the western Cordillera, it has been shown to perform well in an alpine and a coniferous forest environment (DeBeer and Pomeroy 2010; Ellis et al. 2010). CRHM simulated snow accumulation and ablation well relative to 33 other snowpack models, and had a low normalized root mean square error (RMSE) and no outliers when simulating SWE in both clearcut and forested sites (Rutter et al. 2009).

Ellis (2011) demonstrated that CRHM can accurately capture the timing and magnitude of snow accumulation and ablation both under a forest canopy and in clearings. The poorest SWE simulations occurred when accumulation was significantly lower in forest than clearcut sites, due to the greater sensitivity of shallow snowpacks to model errors in energy and mass balance calculations. Modelled SWE was less accurate during the melt period due likely to a melt rate lag, particularly in years with substantial late season snowfall. At a single paired clearing-forest site, CRHM accurately represented the energy balance between the open and sub-canopy snow surface. Errors in radiative flux calculations were small, but generally increased under forest canopy, likely due to the increasing number of combined energy terms. Collective errors in simulating the sum of energy available for snow melt were small and likely due to miscalculations from individual energy terms cancelling each other out.

3.0 Model Inputs

Spatial data describing the vegetation and topographic properties of 241 Cr were obtained from the British Columbia Ministry of Forests, Lands, and Natural Resource Operations as part of the TRIM program. Vegetation data, including distribution, species, tree height, age and stem density files were created through a combination of aerial photo and satellite imagery analyses, and ground sampling. A 25 m digital elevation model (DEM) was created using aerial photography and stereoscopic air photo interpretation. Watershed boundaries, slope, aspect and elevation ranges were derived from the DEM in ArcGIS. These data were then used to divide the watershed into four hydrologic response units (HRUs) with similar aspect, slope, vegetation and elevation range (Fig. A2).

Hourly weather data inputs included air temperature (T_a; °C), relative humidity (*rh*; %), precipitation (*P*; mm), incident shortwave radiation (Q_{si}; W m^{-2}), and wind speed (*u*; m s^{-1}). T_a, *rh*, and *P* were distributed spatially using an air temperature lapse rate (-2.87°C km^{-1}) calculated from measured weather data as the daily average (1999-2008) change in air temperature with elevation between the low and high elevation meteorological stations (P1 and PB, respectively) (Fig. A1). The model corrects incident shortwave radiation for slope and aspect across the basin based on Granier and Ohmura (1970). For the climate sensitivity tests, meteorological input data were varied iteratively as outlined on p. 5 of the preceding report.

Model parameters were defined to represent the physiographic characteristics of each HRU, including elevation, slope, aspect, leaf area index (LAI), and tree height. Parameters were also defined for each process module used in the model. Parameter values were selected from measured field data and from the literature (Tables A2.2 & A2.3). For the climate sensitivity tests, only the mature forest and clearcut scenarios were used. For the forest disturbance tests, the pine beetle and wildfire scenarios were added. Note that a sensitivity test was conducted on model parameters to determine those to which model output was most sensitive (results are not presented here).

Table A2.2. Parameter values for the mature forest and clearcut scenarios.

Parameter	***Mature forest***	***Clearcut***	***Reference***
Tree height (m)*^	17.8	0.25	
Leaf area index (*LAI*)	2.2	n/a	(R. Winkler unpub. data)
Maximum intercepted canopy snow load (*Sbar*; kg m^{-2})	6.6	n/a	(Schmidt and Gluns 1991)
Albedo decay time constant for cold snow (*A1*; s)	9 x 10^5	1 x 10^8	(D. Spittlehouse unpub. data)
Albedo decay time constant for melting snow (*A2*; s)	1 x 10^3	1 x 10^6	(D. Spittlehouse unpub. data)
Initial albedo for bare ground	0.17	0.17	(D. Spittlehouse unpub. data)
Initial albedo for snow cover	0.9	0.9	(Gray and Prowse 1993)
Maximum albedo for fresh snow (α_{max})	0.84	0.84	(Wiscombe and Warren 1980)
Minimum albedo for aged snow (α_{min})	0.36	0.72	(D. Spittlehouse unpub. data)
Minimum snowfall to refresh snow albedo (mm int^{-1})	10	10	(Pomeroy pers. comm.)

***=** Derived from field data

^= HRU definition

Table A2.3. Parameters used for the pine beetle and wildfire scenarios.

Parameter	*Pine beetle*	*Wildfire*	*Referenced in literature or calculated*
Tree height (m)	17.0	15	Calculated from (Burles 2010; R. Winkler unpub. data)
Leaf area index (*LAI*)	1.8	0.4	(Burles 2010; R. Winkler unpub. data)
Maximum intercepted canopy snow load (*Sbar;* kg m^{-2})	5.8	2	Calculated from (Schmidt and Gluns 1991)
Albedo decay time constant for cold snow (*A1*; s)	9×10^6	9×10^6	(D. Spittlehouse unpub. data)
Albedo decay time constant for melting snow (*A2*; s)	100,000	1,000	(D. Spittlehouse unpub. data)
Initial albedo for bare ground	0.17	0.17	(D. Spittlehouse, unpub. data)
Initial albedo for snow cover	0.9	0.9	(Gray and Prowse, 1993)
Maximum albedo for fresh snow (α_{max})	0.80	0.84	(Wiscombe and Warren 1980; Conway et al. 1996; Winkler et al. 2010)
Minimum albedo for aged snow (α_{min})	0.35	0.72	(Wiscombe and Warren 1980; Conway et al. 1996; Winkler et al. 2010; Burles and Boon 2011)
Minimum snowfall to refresh snow albedo (mm int^{-1})	10	10	(Pomeroy, pers. comm.)

4.0 Model Outputs and Analyses

Model output includes hourly calculated values of snow albedo, incoming short- and long-wave radiation, evaporation, incident short- and long-wave radiation at the snow surface, unloaded canopy snow, canopy snow sublimation, snow surface temperature, canopy drip, sensible and latent heat transfer, snowpack cold content, and daily snow melt.

Model performance was assessed for the baseline run using daily average simulated and measured SWE to calculate root mean squared error (RMSE), model bias (MB), mean absolute error (MAE), Nash-Sutcliffe efficiency coefficient (NS), and coefficient of determination (R^2). Each metric was calculated for each individual year in the 9-year dataset, and for the entire dataset.

5.0 References

Beckers J, Smerdon B, Wilson M. 2009. Review of hydrologic models for forest management and climate change applications in British Columbia and Alberta. . FORREX Forum for Research and Extension in Natural Resources, Kamloops, BC, *FORREX Series 25*. www.forrex.org/publications/forrexseries/fs25.pdf

Burles K. 2010. Snowmelt energy balance in a burned forest stand, Crowsnest Pass, Alberta. *MSc Thesis, University of Lethbridge*, Lethbridge, 129 pp.

Burles K, Boon S. 2011. Snowmelt energy balance in a burned forest plot, Crowsnest Pass, Alberta, Canada. *Hydrological Processes* 25(19): 3012-3029.

Conway H, Gades A, Raymond CF. 1996. Albedo of dirty snow during conditions of melt. *Water Resources Research* 32(6): 1713-1718.

DeBeer CM, Pomeroy JW. 2010. Simulation of the snowmelt runoff contributing area in a small alpine basin. *Hydrology and Earth System Sciences* 14: 1205-1219.

Ellis CR, Pomeroy JW, Brown T, MacDonald J. 2010. Simulation of snow accumulation and melt in needleleaf forest environments. *Hydrology and Earth System Sciences Discussions* 7: 1033-1072.

Ellis CR. 2011. Radiation and snowmelt dynamics in mountain forests. *PhD Thesis, University of Saskatchewan*, Saskatoon, SK, 239 pp.

Goodison BE, Ferguson HL, McKay GA. 1981. Measurement and Data Analysis. In: DM Gray and DH Male (Eds), *Handbook of Snow: Principles, Processes, Management and Use*. The Blackburn Press, Caldwell, New Jersey. pp. 191-274.

Granier BJ, Ohmura A. 1970. The evaluation of surface variations in solar radiation income. *Solar Energy* 13: 21-34.

Gray DM, Prowse TD (Eds). 1993. Snow and Floating Ice. *Handbook of Hydrology*. McGraw-Hill, Inc., pp. 7.1-7.58.

Pomeroy JW, Gray DM, Brown T, Hedstrom NR, Quinton WL, Granger RJ, Carey SK. 2007. The cold regions hydrological model: a platform for basing process representation and model structure on physical evidence. *Hydrological Processes* 21: 2650-2667.

Rutter N, Essery R, Pomeroy JW, Altimir N, Andreadis K, Baker I, Barr A, Bartlett P, Boone A, Deng H, Douville H, Dutra E, Elder KJ, Ellis CR, Feng X, Gelfan A, Goodbody A, Gusev Y, Gustafsson D, Hellstrom R, Hirabayashi Y, Hirota T, Jonas T, Koren V, Kuragina A, Lettenmaier DP, Li W, Luce CH, Martin E, Nasonova O, Pumpanen J, Pyles RD, Samuelsson P, Sandells M, Schadler G, Shmakin A, Smirnova TG, Stahli M, Stockli R, Strasser U, Su H, Suzuki K, Takata K, Tanaka K, Thompson E, Vesala T, Viterbo P, Wiltshire A, Xia K, Xue Y, Yamazaki T. 2009. Evaluation of forest snow processes models (SnowMIP2). *Journal of Geophysical Research* 114. doi:10.1029/2008JD011063.

Schmidt RA, Gluns DR. 1991. Snowfall interception on branches of three conifer species. *Canadian Journal of Forest Research* 21: 1262-1269

Winkler R, Boon S, Zimonick B, Baleshta K. 2010. Assessing the effects of post-pine beetle forest litter on snow albedo. *Hydrological Processes* 24: 803-812.

Wiscombe WJ, Warren SG. 1980. A model for the spectral albedo of snow. 1: Pure snow. *Journal of the Atmospheric Sciences* 37: 2712-2733.