Climate change and watershed hydrology: Part II - hydrologic implications for British Columbia

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Research Letters 34, L16503. doi:10.1029/2007GL030780, 2007.

Shabbar, A., B.R. Bonsal, and M. Khandekar. 1997. Canadian precipitation patterns associated with the Southern Oscillation. Journal of Climate 10:3016–3027.

Shabbar, A. and M. Khandekar. 1996. The impact of El Niño Southern Oscillation on the temperature field over Canada. Atmosphere-Ocean 34:401–416.

Spittlehouse, D. 2007. Climate change, impacts and adaptation scenarios. B.C. Ministry of Forests and Range, Victoria, B.C. URL: http://www.for.gov.bc.ca/hts/Future_Forests/Scenarios.pdf

Stewart, I.T., D.R. Cayan, and M.D. Dettinger. 2005. Changes toward earlier streamflow timing across Western North America. Journal of Climate 18:1136–1155.

Stone, D.A., A.J. Weaver, and F.W. Zwiers. 2000. Trends in Canadian precipitation intensity. Atmosphere-Ocean 38(2):321–347.

Storlazzi, C.D., C.M. Willis, and G.B. Griggs. 2000. Comparative impacts of the 1982–3 and 1997–8 El Niño winters on the central California coast. Journal of Coastal Research 16:1022–1036.

Tebaldi, C., K. Hayhoe, J.M. Arblaster, and G.A. Meehl. 2006. Going to the extremes: An intercomparison of model-simulated historical and future changes in extreme events. Climatic Change 79:185–211.

Vincent, L.A. and E. Mekis. 2006. Changes in daily and extreme temperature and precipitation indices for Canada over the twentieth century. Atmosphere-Ocean 44:177–193.

Vincent, L.A., W.A. van Wijngaarden, and R. Hopkinson. 2007. Surface temperature and humidity trends in Canada for 1953–2005. Journal of Climate 20:5100–5113.

Wang, T., A. Hamann, D.L. Spittlehouse, and S.N. Aitken. 2006. Development of scale-free climate data for western Canada for use in resource management. International Journal of Climatology 26:383–397.

Whitfield, P.H. and A.J. Cannon. 2000. Recent variations in climate and hydrology in Canada. Canadian Water Resources Journal 25:19–65.

Zhang, X., K.D. Harvey, W.D. Hogg, and T.R. Yuzyk. 2001. Trends in Canadian streamflow. Water Resources Research 37(4):987–998.

Zhang, X., L.A. Vincent, W.D. Hogg, and A. Niitsoo. 2000. Temperature and precipitation trends in Canada during the 20th century. Atmosphere-Ocean 38:395–429.

Climate Change and Watershed Hydrology: Part II – Hydrologic Implications for British Columbia

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The accompanying article described recent climate changes in British Columbia. These changes are likely to result in adjustments in watershed hydrology and ultimately in our use of water-related resources. Increased risks of droughts, floods, and landslides will likely result in considerable socio-economic, biological, and physical changes. Future climate change will bring about greater changes and challenge our management of forest and range resources (Spittlehouse and Stewart 2003). To adapt to and in some cases mitigate the effects of climate change, it is necessary to understand the hydrologic implications for the future. This article (Part II) discusses eight broad hydrologic implications of climate change in British Columbia.

Hydrologic Implications for British Columbia

As a result of current trends and future climate projections, the following high-level hydrologic-related changes may be expected to occur:

- increased atmospheric evaporative demand;
- altered vegetation composition affecting evaporation and interception;
- increased stream/lake temperatures;
- increased frequency/magnitude of storm events and disturbances;
- decreased snow accumulation and accelerated melt;
- accelerated melting of permafrost, lake ice, and river ice;
- glacier mass balance (advance/recession) adjustments; and
- altered timing and magnitude of streamflow (peak flows, low flows).

Increased Atmospheric Evaporative Demand

The climate scenarios previously described could increase the atmosphere's ability to evaporate water (Huntington 2008). This will occur if the saturated vapour pressure of the air (a function of air temperature) increases more rapidly than the actual vapour pressure (i.e., the vapour pressure deficit increases). It will also increase if net radiation and wind speed increase. An increase in evaporative demand would significantly affect water resources through evaporative losses from streams, lakes, and reservoirs, and changing water demand for irrigation. It will also affect vegetation survival and growth through changes in water availability and likely increased fire risk. For example, Spittlehouse (2007) determined the magnitude of change in evaporative demand (calculated following Allen *et al.* 1998; Moore *et al.* 2008) for the Campbell River, Cranbrook, and Fort St. John areas using current weather station data and climate change data for the B1 and A2 scenarios from the Canadian GCM. Evaporative demand, which is calculated for months when the air temperature is above 0°C, increased at all locations due to an increase in the length of the time the air temperature was above 0°C and to an increase in the vapour pressure deficit (drier air). By the 2080s, evaporative demand will increase by about 8% under the B1 scenario and by 15–20% under the A2 scenario.

Estimates of the evaporative demand and precipitation can be combined to give indicators of plant water stress and to predict water demand for agricultural irrigation and domestic use. A climatic moisture deficit occurs if the monthly precipitation is less than the evaporative demand for the month; if precipitation is greater than the evaporative demand, there is a moisture surplus. By the 2080s under the B1 scenario, Spittlehouse (2007) reported that the deficit at Campbell River increased by 20%, at Fort St John by 25%, and at Cranbrook by 30%. For the A2 scenario, Campbell River and Fort St John increased by 30% while Cranbrook increased by 60%. The larger increase at Cranbook reflects the decrease in summer rainfall and an initially relatively low average deficit for 1961 to 1990 reference period. A moisture surplus did not occur during the summer at any of the locations (Spittlehouse 2007).

As vegetation composition responds to climate change, so too will the amounts of water intercepted, evaporated, and transpired, thus altering water balance and ultimately streamflow.

Altered Vegetation Composition Affecting Evaporation and Interception

Terrestrial vegetation influences water balance through the interception of precipitation and the removal of water from the root zone through plant transpiration and evaporation from the soil surface. As vegetation composition responds to climate change, so too will the amounts of water intercepted, evaporated, and transpired, thus altering water balance and ultimately streamflow. Increases in the length of the snow-free season and changes in atmospheric evaporative demand are likely to increase plant transpiration assuming soil water is available. For example, Spittlehouse (2003) estimated that transpiration from a coastal Douglas-fir forest could rise by 6% for a 2°C increase and 10% for a 4°C increase in temperature. Projected changes in climate are sufficient to affect forest productivity and the species that could grow on a site (Barber *et al.* 2000; Hamann and Wang 2006; Campbell *et al.* 2008). There may also be changes in age-class distribution and in the form of vegetation (e.g., forest die-off, alpine encroachment, grassland expansion) (Breshears *et al.* 2005; Hebda 2007; Campbell *et al.* 2008). Thus the amount of plant material on a site and the physiological characteristics of the new vegetation will have an important effect on water balance.

Increased Stream/Lake Temperatures

Stream and lake temperatures are projected to increase due to climate change, which can result in a number of specific concerns for water and fish species, including salmon (Levy 1992; Mote *et al.* 2003). The vulnerability of fish to change will depend on how much the water body warms and the sensitivity of individual fish species to temperature. Responses to increased temperature will generally be defined by fish species or specific stocks, and how these changes will affect the various life stages (from egg to spawning adult). Increased temperatures in temperature-sensitive systems may result in increased frequencies of disease, increased energy expenditures, altered growth, thermal barriers to both adult and juvenile migration, delayed spawning, reduced spawner survival, altered egg and juvenile development, changes in biological productivity and other rearing conditions, and altered species distribution.

Watersheds with warm water temperatures or low flows that currently affect salmonid survival are centred in the southwest, southern Interior, and central Interior of British Columbia (Nelitz *et al.* 2007). Under a changing climate, it is projected these areas will be further stressed. Salmonids show species-specific thermal optima and tolerances (Selong *et al.* 2001; Bear *et al.* 2007); even small (1–2°C) differences in these parameters may result in marked differences in species distribution (Fausch *et al.* 1994). Distribution changes may be the direct result of the effects of water temperature on fish physiology or indirectly a consequence of displacement of temperature-sensitive species such as bull trout (*Salvelinus confluentus*) by competing species such as rainbow trout (*Oncorhynchus mykiss*). Therefore, shifts in population distributions may be unavoidable and likely will result in the loss of salmonids in some areas where habitat conditions are currently close to tolerable limits (Nelitz *et al.* 2007). The effects of increased water temperatures are likely to be compounded wherever hydrologic regime changes reduce seasonal flows. For example, the limits of fish distribution in headwater areas can be further altered with changes in the abundance and distribution of perennial, intermittent, and ephemeral watercourses.

Alternatively, in regions or specific water bodies where current temperatures are below thermal optima for fish, or temperature sensitivity is not a concern, increased water temperatures may promote fish growth and survival. Even minor temperature increments can change egg hatch dates and increase seasonal growth and in-stream survival in juvenile salmon. At Carnation Creek, minor changes in stream temperatures in the fall and winter due to forest harvesting profoundly affected salmonid populations, accelerating egg and alevin development rates, emergence timing, seasonal growth, and the tim-

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ing of seaward migration (Tschaplinski *et al.* 2004). A useful species and life stage specific summary of potential biological vulnerabilities to climate-induced changes in water flows and temperatures can be found in Nelitz *et al.* (2007).

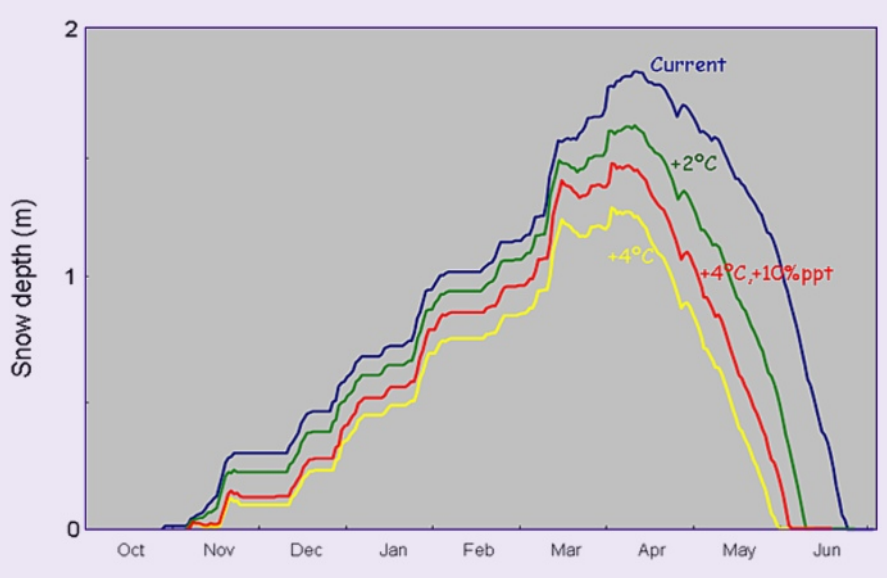

Figure 1. Simulated winter snow depth for Glacier National Park, Rogers Pass under current (winter 2001/02) temperature and precipitation (blue line) and three climate change scenarios. The scenarios are 2°C warming (increase to daily temperature record for winter 2001/02) with no precipitation change (green line), 4°C warming with no change in precipitation (yellow line), and 4°C warming and a 10% increase in precipitation (red line). Winter 2001/02 had close to average October to April precipitation and snow on the ground at the end of March and April for Glacier. Source: Spittlehouse (2007).

Increased Frequency/Magnitude of Storm Events and Disturbances

Storm frequency and intensity are projected to increase (IPCC 2007), likely raising the frequency of windthrow, breakage of trees, and flooding. An increase in the intensity of storms could also increase the frequency of the occurrence of landslides (Miles 2001). Landslides in British Columbia are largely driven by climate, but respond differently depending on the type of landslide and initiating process (Geertsema *et al.* 2007). In northern British Columbia, shallow slides and debris flows happen during infrequent large storms; large rock slides appear to respond to warming and may be triggered during convective storms; larger soil slides are more common during periods of increasing precipitation (Egginton *et al.* 2007; Geertsema *et al.* 2007). Prolonged periods of increased precipitation or temperature increase the vulnerability of slopes to failure. This is due to soil saturation and (or) destabilization from melting snow or ice, which is expected to be further enhanced under current climate change scenarios. For the Georgia Basin, Miles (2001) reported that a 10% increase in annual precipitation over 80 years could affect the average return period between 24-hour rainfall events and events large enough to initiate slope failures could decrease from 10.4 to 6.3 years. Fluctuating winter temperatures and storm cycles may also increase avalanche activity. The implications of increased incidence of disturbance events can lead to increased rates of erosion/sedimentation, increased number of landslide-derived log jams, increased channel destabilization, and eventually decreased large woody debris supply from the channel banks, ultimately affecting stream channel form and riparian function. Changes to the return period of events also have implications for engineering design criteria.

All of these altered processes and frequencies have implications for stream ecology and fish populations. Disturbances such as landslides and debris flows directly connected to stream channels reduce the quantity and quality of fish habitats, and consequently the local abundance of salmon populations in impacted stream reaches (Hartman and Scrivener 1990; Tschaplinski *et al.* 2004). Additionally, related processes such as local streambed scour (degradation) can isolate the main stream channel from important seasonal fish habitats and refuges located in the floodplain, thus potentially reducing salmon survival and annual smolt production (Hartman and Scrivener 1990; Tschaplinski *et al.* 2004).

Decreased Snow Accumulation and Accelerated Melt

Increased temperatures as a result of climate change will lead to a continued decrease in snow accumulation (Rodenhuis *et al.* 2007), earlier melt (Figure 3), and less water storage for spring freshet (Stewart *et al.* 2004) and (or) to release to groundwater storage in British Columbia. The projected declines are most notable in the central and northern Coast of British Columbia and at high-elevation sites along the South Coast (Rodenhuis *et al.* 2007). The anticipated greater warming in the winter than the summer will impact snow levels. Average snowlines will migrate north in latitude and up in elevation in response to increasing temperatures with time. Watersheds that would be the most sensitive to change are those occupying the border between rainfall and snow deposition in the winter (mixed regimes). With projections of concurrent increases in precipitation, this thermal effect will be somewhat offset compared with changes resulting from increased temperature alone (Figure 1). However, if a large portion of winter precipitation shifts to rain, the amount and timing of discharge (see Streamflow discussion below) will significantly change. It is expected that decreased storage of winter precipitation will likely reduce the magnitude of the spring peak flow, and exacerbate summer low-flow conditions. Hydrologic scenarios for snowmelt-dominated basins in the Okanagan were projected to change in this way (Merritt *et al.* 2006); however, the degree of change projected depended on the GCM used. Changes in seasonal snow accumulation and melt will result in changes to the streamflow regime, which has important implications for water supply, hydroelectric power, fish, and aquatic habitat. Less snow also has major implications for winter recreation.

Accelerated Melting of Permafrost, Lake Ice, and River Ice

Rising temperatures will be affect Ice-related hydrologic features . Projections of milder winter temperatures mean that river and lake ice could occur later and disappear earlier than normal. These hydrologic changes will have implications on forest harvest scheduling (operable ground, seasonal water tables, timing), transportation (ice bridges), and recreation (fishing opportunities). Recent analysis has shown that permafrost in many regions of North America is also warming (Brown *et al.* 2004); in northern British Columbia, discontinuous permafrost can also be expected to respond to changes in temperature and precipitation. Like glaciers, not all permafrost in existence today is in equilibrium with the present climate. Unlike glaciers, adjustment to present climate lags on a longer time scale due to the insulating effects of the ground. In the discontinuous permafrost region, where ground temperatures are within 1–2°C of melting, permafrost will likely disappear as a result of ground thermal changes associated with global warming (NRCAN 2006). In areas where the ice content is high, thawing of permafrost can lead to increased thaw settlement and thermokarst activity, while reduced soil strength in response to melt will lead to ground instability, increasing the incidence of slope failures (Smith and Burgess 2004). The integrity of engineered structures such as bridge footings, building foundations, roads, railways, and pipelines will also be affected (Woo *et al.* 2007). The overall thermal response of permafrost to increased temperatures will depend on surface buffer factors such as snow, vegetation, and organic ground cover that can attenuate temperature changes (Smith and Burgess 2004).

Glacier Mass Balance (Advance/Recession) Adjustments

Given the future climate change projections, it is expected that most glaciers in British Columbia will continue to recede, except those at the coldest locations (Rodenhuis *et al. 2007).* Hall and Fagre (2003) modelled glacier dynamics in Montana's Glacier National Park under two scenarios. In the first, with a doubling of CO^2, all glaciers disappeared by 2030. In the second, with a linear increase in temperature over time, glaciers remained until 2277. In British Columbia's southern Rocky Mountains, Parks Canada (2005) predicts that glaciers less than 100 m thick will disappear within 20 years. The effects of these changes impact hydrologic function and in some cases hydrologic regimes. Negative glacier mass balance should result in increased summer streamflows for some years or decades as glacier melt accelerates due to warming temperatures. This effect will be followed by a larger decrease when the glaciers eventually disappear, or drop to some small proportion of the watershed area. The reduction to elimination of the glacial melt streamflow component that augments summer low flows in many watersheds will result in more low-flow days on these streams. Already, evidence supports this hypothesis. Stahl and Moore (2006) reported that, since 1970, glacier-fed streams in British Columbia have exhibited a decreasing trend for August streamflow. Future projections of August streamflow in the 2050s for Bridge River show marked reductions in glacier area and summer streamflow, even assuming that the present climate continues. These trends are even stronger for the warming scenarios downscaled from GCM simulations, decreasing by 37% (Stahl *et al.* 2008).

Altered Streamflow (Peak Flows, Low Flows)

Streamflow regimes are controlled primarily by watershed geology and seasonal patterns of temperature and precipitation. British Columbia has four primary hydrologic regimes: (1) rain-dominated, (2) snowmelt-dominated, (3) mixed/hybrid, and (4) glacier-augmented (Eaton and Moore 2007). The relative importance of climatic changes, therefore, will vary by region depending on the current sensitivity to regional temperature and precipitation changes. Also, groundwater storage and release strongly control streamflow (e.g., low flows) in some watersheds. Variations in underlying geology that influence whether snowmelt goes into groundwater reserves or into direct runoff can strongly influence the magnitude and timing of late summertime streamflow and thus influence the magnitude of the response to climate change (Thompson 2007).

Rain-dominated (sometimes called pluvial) regimes closely follow the seasonal pattern of precipitation. These regimes are found mostly in lowland and coastal areas in British Columbia. Rain-dominated regimes typically experience peak flows in the winter, with low flows occurring in summer. Snowmelt-dominated (nival) regimes occur in the Interior Plateau and mountain region and at higher elevations in the Coast Mountains (Eaton and Moore 2007). Snowmelt-dominated regimes typically experience peak flows in the spring (as a result of snowmelt) with low flows in the late summer extending through the winter during the snow accumulation period. Watersheds that display the characteristics of both of these regimes are referred to as mixed or hybrid regimes (Eaton and Moore 2007). These

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regimes can have significant streamflow (peaks) in both winter (as a result of rain) and spring (as a result of snowmelt from higher elevations). Low flows occur in summer in these watersheds. Hydrographs of glacier-fed (glacier-augmented) streams are similar in shape to those of snowmelt-dominated watersheds, except the low-flow period begins later in the summer to early fall due to the extra summer contributions from glacial meltwater.

The hydrologic effects of climate change will likely have an important impact on watersheds where cold-season precipitation is stored in snowpacks. The response of rain-dominated regimes will likely follow predicted changes in precipitation (Loukas *et al.* 2002). For example, an increased magnitude and frequency of storm events will result in an increased frequency and magnitude of storm-driven peak flows in the winter. In the summer, projected drier summers raise concerns around increased number and magnitude of low-flow days.

Projected warming will result in less snow stored over winter, and more winter precipitation will fall as rain. In these situations, mixed/hybrid regimes might transition to rain-dominated regimes through the weakening or elimination of the snowmelt component (Whitfield *et al.* 2002; Eaton and Moore 2007). Similarly, snowmelt-dominated watersheds might exhibit characteristics of hybrid regimes and glacial-augmented systems might shift to a more snowmelt-dominated pattern in the timing and magnitude of annual peak flows and low flows. For example, in the southern Columbia Mountains at Redfish Creek, there has been an observed increase in the incidence of fall–early winter peak streamflow events that up to 10 years ago were relatively rare in the hydrometric record (P. Jordan, pers. comm., Dec. 2007). With the projected elevated temperatures, there will be a shorter snow-accumulation season and likely an earlier start to the spring freshet in snowmelt-dominated systems, which may lengthen the period of late summer and early autumn low flows (Loukas *et al.* 2002; Merritt *et al.* 2006). In watersheds where snow is the primary source for summer streamflow, loss of winter snowpack may reduce the late summer drainage network, with perennial streams becoming intermittent (Thompson 2007). Conversely, watersheds where groundwater is the source of summertime streamflow will still continue to flow, albeit under reduced volumes (Thompson 2007) in response to changes in seasonal snowpack accumulation that recharge groundwater.

In hybrid-regime watersheds on the coast, snowpacks above 1000–1200 m can be up to 4–5 m in depth (e.g., Russell Creek), especially in north-facing open bowls or subalpine forests (B. Floyd, pers. comm., 2007). Snowpacks in these hybrid regimes can be deep enough to store a significant amount of rain, thus dampening the response of watersheds to large midwinter rain events. If these snowpacks no longer form or are very shallow and are coupled with increases in temperature, large midwinter snowfall events will change to large rain events, thereby increasing the frequency of peak flows occurring throughout the winter in these watersheds. Subsequently, spring peak flows will be reduced and occur earlier due to less precipitation being stored as snow during the winter, and winter flows will be greater if precipitation falls as rain instead of snow.

In glacier-augmented systems, as previously discussed, peak flows would decrease and occur earlier in the year, similar to snowmelt-dominated regimes. In the long term, the reduction or elimination of the glacial meltwater component in the summer/early fall would increase the frequency and duration of low-flow days in these systems.

Conclusion

British Columbia's climate has changed over the last 100 years and will continue to shift. The accompanying changes and the associated hydrologic implications will have many important implications for fisheries, agriculture, forestry, recreation, hydroelectric power, and water resources, yet these changes will vary in importance according to local conditions. The projected impacts of climate change on streamflow will vary across the province and hence local mitigation and adaptation strategies will likely be needed to ensure the effective stewardship of watershed resources and associated values.

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References

Allen, R.G., L.S. Pereira, D. Raes, and M. Smith. 1998. Crop evapotranspiration - Guidelines for computing crop water requirement. U.N. Food and Agriculture Organization, Rome. FAO Irrigation and Drainage Paper FAO56.

Barber, V.A., G.P. Juday, and B.P. Finney. 2000. Reduced growth of Alaskan white spruce in the twentieth century from temperature-induced drought stress. Nature 405:668–673.

Bear, E.A., T.E. McMahon, and A.V. Zale. 2007. Comparative thermal requirements of westslope cutthroat trout and rainbow trout: Implications for species interactions and development of thermal protection standards. Transactions of the American Fisheries Society 136:1113–1121.

Breshears, D.D., N.S. Cobb, P.M. Rich, K.P. Price, C.D. Allen, R.G. Balice, W.H. Romme, J.H. Kastens, M.L. Floyd, J. Belnap, J.J. Anderson, O.B. Myers, and

C.W. Meyer. 2005. Regional vegetation die-off in response to global-change-type drought. Proceedings of the National Academy of Science 102:15144–15148.

Brown, R.D., M.N. Demuth, B.E. Goodison, P. Marsh, T.D. Prowse, S.L. Smith, and M.K. Woo. 2004. Climate variability and change – cryosphere. In Threats to water availability in Canada. National Water Research Institute. Meteorological Service of Canada. Environment Canada, National Water Research Institute, Scientific Assessment Report Series No. 3, pp. 107–116.

Campbell, E., D. Meidinger, S. Saunders, D. Morgan, G. O'Neil, A. MacKinnon, C. Delong, B. Rogers, D. MacKillop, M. Kranabetter, R. Pike, P. Tschaplinski, J. Burleigh, and D. Spittlehouse. 2008. A scientific foundation for the Future Forest Ecosystems Initiative of British Columbia. Forest Science Program B.C. Forest Service. URL: http://www.for.gov.bc.ca/hts/Future_Forests/

Eaton, B. and R.D. Moore. 2007. Chapter 4 – Regional hydrology [draft]. In Compendium of forest hydrology and geomorphology in British Columbia. R.G. Pike et al. (editors). B.C. Ministry of Forests and Range, Research Branch, Victoria, B.C. and FORREX Forest Research Extension Partnership, Kamloops, B.C. Land Management Handbook. In preparation. URL: http://www.forrex.org/program/water/compendium.asp

Egginton, V., J. Clague, and P. Jackson. 2007. Using weather imagery to identify potential landslide triggers in northern British Columbia. Streamline Watershed Management Bulletin 11:17–21.

Fausch, K.D., S. Nakano, and K. Ishigaki. 1994. Distribution of two congeneric charrs in streams of Hokkaido Island, Japan: Considering multiple factors across scales. Oecologia 100:1–12.

Geertsema, M., V.N. Egginton, J.W. Schwab, and J.J. Clague. 2007. Landslides and historic climate in northern British Columbia. In Landslides and climate change: Challenges and solutions, Proceedings from the International Conference on Landslides and Climate Change, Ventor, Isle of Wight, U.K., May 21–24, 2007, pp. 9–16.

Hall, M.P. and D.B. Fagre. 2003. Modeled climate-induced glacier change in Glacier National Park, 1850–2100. Bioscience 53:131–140.

Hamann, A. and T. Wang. 2006. Potential effects of climate change on ecosystem and tree species distribution in British Columbia. Ecology 87:2773–2786.

Hartman, G.F. and J.C. Scrivener. 1990. Impacts of forestry practices on a coastal stream ecosystem, Carnation Creek, British Columbia. Canadian Bulletin of Fisheries and Aquatic Sciences 223.

Hebda, R.J. 2007. Ancient and future grasslands: Climate change and insights from the fossil record and climate models. BC Grasslands 11:14–16.

Huntington, T.G. 2008. CO^{2}-induced suppression of transpiration cannot explain increased runoff. Hydrological Processes 22:311–314.

Intergovernmental Panel on Climate Change (IPCC). 2007. Climate change 2007: The physical science basis: Summary for policymakers. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change, Geneva, 23 p. URL: http://www.ipcc.ch

Levy, D.A. 1992. Potential impacts of global warming on salmon production in the Fraser River watershed. Canadian Technical Report on Fisheries and Aquatic Sciences 1889. 96 p.

Loukas, A., L. Vasiliades, and N.R. Dalezios. 2002. Climatic impacts on the runoff generation processes in British Columbia, Canada. Hydrology and Earth Systems Science 6:211–227.

Merritt, W.S., Y. Alila, M. Barton, B. Taylor, S. Cohen, and D. Neilsen. 2006. Hydrologic response to scenarios of climate change in sub watersheds of the Okanagan basin, British Columbia. Journal of Hydrology 326:79–108.

Miles, M. 2001. Effects of climate change on the frequency of slope instabilities in the Georgia Basin, B.C. – Phase 1. Report prepared for Canadian Climate Action Fund, Natural Resources Canada, Ottawa, Ont.

Moore, R.D., D.L. Spittlehouse, P. Whitfield, and K. Stahl. 2008. Chapter 3 – Weather and climate [draft]. In Compendium of forest hydrology and geomorphology in British Columbia. R.G. Pike et al. (editors). B.C. Ministry of Forests and Range, Research Branch, Victoria, B.C. and FORREX Forest Research Extension Partnership, Kamloops, B.C. Land Management Handbook. In preparation. URL: http://www.forrex.org/program/water/compendium.asp

Mote, P.W., E.A. Parson, A.F. Hamlet, W.S. Keeton, D. Lettenmaier, N. Mantua, E.L. Miles, D.W. Peterson, D.L. Peterson, R. Slaughter, and A.K. Snover. 2003. Preparing for climate change: The water, salmon and forests of the Pacific Northwest. Climate Change 61:45–88.

Natural Resources Canada (NRCAN). 2006. Permafrost and climate change. Web site. URL: http://gsc.nrcan.gc.ca/permafrost/climate_e.php (Accessed October 24, 2007).

Nelitz, M., K. Wieckowski, D. Pickard, K. Pawley, and D.R. Marmorek. 2007. Helping Pacific salmon survive the impact of climate change on freshwater habitats. Final report prepared by ESSA Technologies Ltd., Vancouver, B.C. for Pacific Fisheries Resource Conservation Council, Vancouver, B.C. 128 p. URL: http://www.fish.bc.ca/files/PFRCC-ClimateChange-Adaptation.pdf

Parks Canada. 2005. "The Climate Is Changing Our National Parks". Web site: URL: http://www.pc.gc.ca/docs/v-g/ie-ei/cc/index_E.asp

Rodenhuis, D., K.E. Bennett, A. Werner, T.Q. Murdock, and D. Bronaugh. 2007. Hydro-climatology and future climate impacts in British Columbia. Pacific Climate Impacts Consortium. URL: http://www.pacificclimate.org/publications/PCIC.ClimateOverview.pdf

Selong, J.H., T.E. McMahon, A.V. Zale, and F.T. Barrows. 2001. Effect of temperature on growth and survival of bull trout, with application of an improved method for determining thermal tolerance in fishes. Transactions of the American Fisheries Society 130:1026–1037.

Smith, S.L. and M.M. Burgess. 2004. Sensitivity of permafrost to climate warming in Canada. Ottawa, Ont. Geological Survey of Canada Bulletin 579.

Spittlehouse, D.L. 2003. Water availability, climate change and the growth of Douglas-fir in the Georgia Basin. Canadian Water Resources Journal 28:673–688.

_______. 2007. Climate change, impacts and adaptation scenarios. B.C. Ministry of Forests and Range, Victoria, B.C. URL: http://www.for.gov.bc.ca/hts/Future_Forests/Scenarios.pdf

Spittlehouse, D.L. and R.B. Stewart. 2004. Adaptation to climate change in forest management. BC Journal of Ecosystems and Management 4(1):7–17. URL: http://www.forrex.org/jem/2003/vol4/no1/art1.pdf

Stahl, K. and R.D. Moore. 2006. Influence of watershed glacier coverage on summer streamflow in British Columbia, Canada. Water Resources Research 42, W06201. doi: 10.1029/2006WR005022.

Stahl, K., R.D. Moore, J.M. Shea, D. Hutchinson, A.J. Cannon. 2008. Coupled modelling of glacier and streamflow response to future climate scenarios, Water Resources Research 44, W02422, doi:10.1029/2007WR005956.

Stewart, I.T., D.R. Cayan, and M.D. Dettinger. 2004. Changes in snowmelt runoff timing in western North America under a "business as usual" climate change scenario. Climatic Change 62:217–232.

Thompson, J. 2007. Running dry: Where will the west get its water? Science Findings Issue 97, October 2007. URL: http://www.fs.fed.us/pnw/sciencef/scifi97.pdf

Tschaplinski, P.J., D.L. Hogan, and G.F. Hartman. 2004. Chapter 18: Fish-forestry interaction research in coastal British Columbia – the Carnation Creek and Queen Charlotte Islands studies. In Fishes and forestry: Worldwide watershed interactions and management. T.G. Northcote and G.F. Hartman (editors). Blackwell Science Ltd.

Whitfield, P.H., C.J. Reynolds, and A.J. Cannon. 2002. Modelling streamflows in present and future climates – examples from the Georgia Basin, British Columbia. Canada Water Resources Journal 27(4):427–456.

Woo, M.K., M. Mollinga, and S.L. Smith. 2007. Climate warming and active layer thaw in the boreal and tundra environments of the Mackenzie Valley. Canadian Journal of Earth Sciences 44(6):733–743.