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Glacier change in western North America: influences on hydrology, geomorphic hazards and water quality

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Abstract:

The glaciers of western Canada and the conterminous United States have dominantly retreated since the end of the Little Ice Age (LIA) in the nineteenth century, although average rates of retreat varied from strong in the first-half of the twentieth century, with glaciers stabilizing or even advancing until 1980, and then resuming consistent recession. This retreat has been accompanied by statistically detectable declines in late-summer streamflow from glacier-fed catchments over much of the study area, although there is some geographical variation: over recent decades, glaciers in northwest BC and southwest Yukon have lost mass dominantly by thinning with relatively low rates of terminal retreat, and glacier-fed streams in that region have experienced increasing flows. In many valleys, glacier retreat has produced geomorphic hazards, including outburst floods from moraine-dammed lakes, mass failures from oversteepened valley walls and debris flows generated on moraines. In addition to these hydrologic and geomorphic changes, evidence is presented that glacier retreat will result in higher stream temperatures, possibly transient increases in suspended sediment fluxes and concentrations, and changes in water chemistry. With climate projected to continue warming over the twenty-first century, current trends in hydrology, geomorphology and water quality should continue, with a range of implications for water resources availability and management and hydroecology, particularly for cool and cold-water species such as salmonids. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS glacier change; climate change; streamflow; water quality; geomorphic hazards

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INTRODUCTION

Glaciers are sensitive indicators of climate change and an important natural resource in western North America (Østrem, 1966; Meier, 1969). In British Columbia (BC) alone, for example, glaciers cover 3% of the landmass (30 000 km^2) and serve as frozen freshwater reservoirs that supplement snowmelt and rainfall runoff during summer and early autumn. Glaciers represent a substantial source of renewable energy, contribute to the sustainability of ecosystems, and bolster the tourism economy in both the United States and Canada.

In the Canadian Cordillera, glaciers and icecaps are primarily located in the Coast (22 000 km^2) and St Elias mountains (4300 km^2), along with smaller areas in the Rocky Mountains (2300 km^2), the Columbia, Selkirk and Cariboo ranges in the southern interior (1900 km^2), and the Stikine, Skeena and Babine ranges in the northern interior (540 km^2). In addition, a small number of cirque glaciers totalling less than 30 km^2 are in the Insular Mountains of Vancouver Island [approximate areas from BC Terrain Resource Inventory Management (TRIM) database]. In the conterminous United States, glaciers cover about 688 km^2 across eight states, with Washington State having the largest concentration of glaciers, totalling 450 km^2 (Fountain *et al.*, 2007).

Glaciers have a profound influence on streamflow and water quality over a range of time scales—diurnal, seasonal, inter-annual, decadal and longer (Fountain and Tangborn, 1985; Lafrenière and Sharp, 2003; Stahl and Moore, 2006). Glaciers throughout western North America have generally retreated since the end of the Little Ice Age (LIA) in the nineteenth century, though some glaciers advanced during cool, wet decades of the twentieth century. As a result, the nature of the streamflow response to climatic variability will have varied through time, with the consequence that past data may not accurately represent future conditions. This concern about non-stationarity becomes even more severe with the prospect that future climate warming, itself a major cause of non-stationarity (Milly *et al.*, 2008), may accelerate glacier retreat (IPCC, 2007). The objective of this paper is to review what is currently known about historic glacier variations in western North America and their effects on streamflow, geomorphic hazards and water quality. In addition, we examine the

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prospects for future conditions, including the effects of future climatic change. Finally, we touch on some of the implications for water resources and aquatic ecology, particularly salmonids. The geographic focus includes glacierized mountain regions of the conterminous United States [focusing on the Pacific Northwest (PNW) region], BC, southwest Yukon, Alberta and southeast Alaska (Figure 1).

CLIMATIC VARIABILITY AND CHANGE IN WESTERN NORTH AMERICA

The winter climate of western North America is dominated by a progression of cyclonic storms that migrate from west to east across the Pacific Ocean and generate a large proportion of the total annual precipitation. In summer, the storm tracks shift north, and anticyclonic systems associated with warm, dry weather occur more frequently, particularly in the US PNW and southern BC. Strong precipitation gradients occur with both elevation and distance from the coast, in addition to regional temperature gradients with distance from the coast, elevation and latitude, resulting in contrasts between the temperate maritime Cascades and Coast Mountains, the subarctic maritime St Elias Mountains and the continental Rocky Mountains.

Regional atmospheric circulation during winter is typically dominated by one of the two phases of the Pacific North America (PNA) pattern, which is a natural, internal mode of atmospheric circulation variability over the North Pacific and North America (Wallace and Gutzler, 1981). The strong or enhanced (positive) phase is characterized by southerly air flow along the west coast of North America with a ridge of high pressure over the Rocky Mountains. The weak (negative) phase is dominated by westerly, zonal flow. Winter climate in the US PNW and southern BC is strongly linked to PNA. The weak phase tends to produce cooler and wetter weather than the enhanced phase and higher snow accumulation in southern BC and the US PNW, especially in maritime locations (Greenland, 1995; Moore and McKendry, 1996; Moore, 1996).

Other large-scale influences on the hydroclimate of western North America include the El Niño-Southern

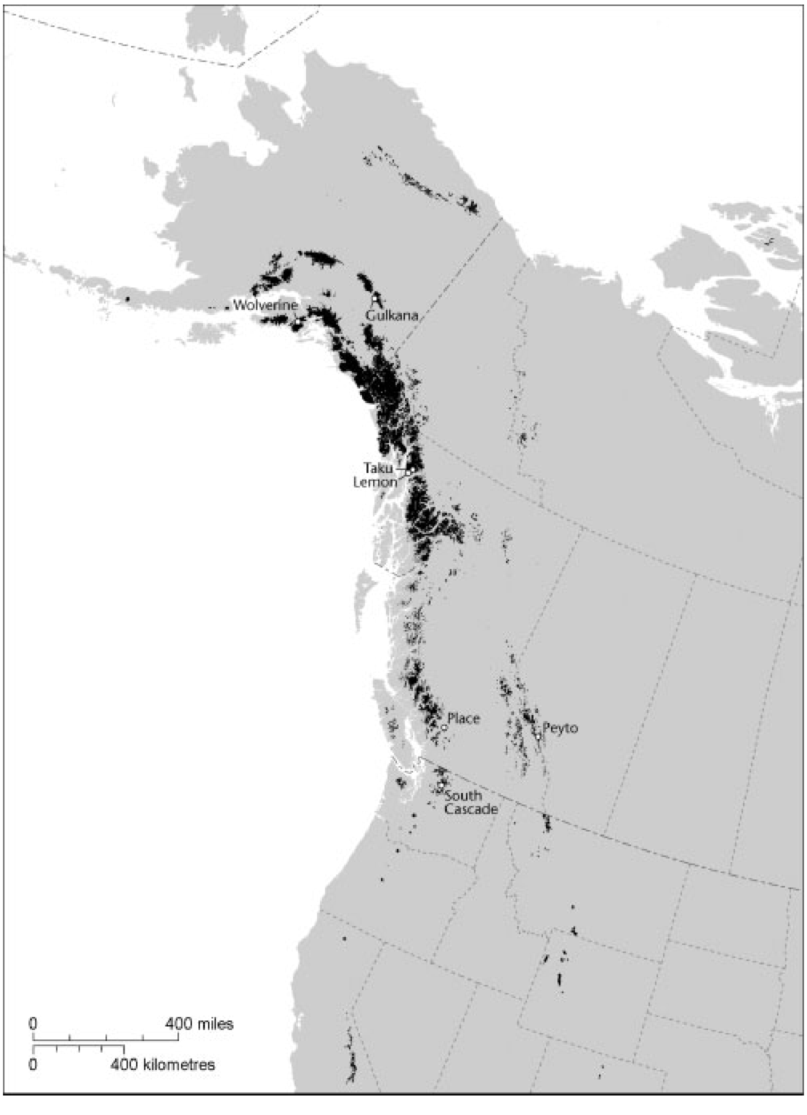

Figure 1. Map of the glacierized regions of western North America. Locations of long-term mass balance sites used to construct Figure 2 are shown

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Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO). The dominant expression of ENSO is through changes in sea-surface temperatures (SSTs) in the eastern equatorial region of the Pacific Ocean, with phase changes typically occurring every 2–7 years. The PDO index represents the time series scores of the leading principal component for North Pacific SSTs. The warm-phase of PDO is dominated by higher-than-average SSTs along the west coast of North America and lower-than-average SSTs in the central North Pacific; the cool phase has the opposite anomaly pattern. In contrast to ENSO, PDO changes phase every two to three decades, with documented shifts occurring about 1922, 1947 and 1977 (Mantua *et al*., 1997). In addition, a shift in Pacific climate apparently occurred in 1989, which was expressed most strongly in marine biological indicators (Hare and Mantua, 2000). The enhanced phase of PNA tends to occur more frequently during the warm phases of the ENSO and the PDO, particularly when ENSO and PDO are in phase (Renwick and Wallace, 1996; Yu and Zwiers, 2007). The weak phase of PNA is favoured during the cool phases of ENSO and PDO.

Another mode of climatic variability that influences at least the northern portions of western North America is the Arctic Oscillation (AO). The AO is a hemispheric scale, but primarily higher-latitude, meridional seesaw in atmospheric mass between the Arctic and mid-latitudes (Thompson and Wallace, 1998). It appears to be associated with fluctuations in the strength of the winter stratospheric polar night jet. Whereas the PNA, ENSO and PDO are in some sense mutually related, the AO is linearly independent of these Pacific-oriented phenomena; however, non-linear relations may exist (Wu and Hsieh, 2004).

The LIA ended in the mid- to late-nineteenth century in western North America (Davis, 1988; Osborn and Luckman, 1988; Luckman, 2000). Since then, the regional climate has been dominated by a warming trend. Over the twentieth century, annual temperatures exhibited trends of about $+0{\cdot}5$ to $+1{\cdot}5\,^{\circ}$C per century, with greater warming at night and in winter (e.g. Zhang *et al*., 2000; Mote, 2003; Rodenhuis *et al*., 2007). Overlaid on this warming trend have been shorter-term climate fluctuations associated with, for example, ENSO variations and PDO shifts. General circulation models (GCMs) consistently indicate that the warming trend should continue and likely increase in magnitude over the next century under all the proposed emission scenarios (IPCC, 2007). There is less consistency in GCM projections for precipitation, although some studies suggest the changes in annual precipitation will be relatively modest (e.g. Mote *et al*., 2005; Rodenhuis *et al*., 2007; Stahl *et al*., 2008). Seasonality of precipitation changes varies among GCMs and regions, but the tendency among projections is for wetter winters and drier summers throughout southern BC and the US PNW; northern BC is projected to become wetter in both winter and summer (Rodenhuis *et al*., 2007).

RECENT GLACIER CHANGE

Variations in glacier mass balance

Direct measurements of mass balance in western North America have been conducted at a relatively small number of sites and for relatively short periods. Continuing measurements of glacier mass balance in the study region began at the Juneau Icefield with the establishment of annual net balance surveys at Taku Glacier in 1946 and Lemon Creek Glacier in 1953 (Pelto and Miller, 1990; Marcus *et al*., 1995) In 1953, the US Geological Survey (USGS) began monitoring mass balance at South Cascade Glacier, Washington (Meier and Tangborn, 1965). Mass balance measurements were initiated at Blue Glacier in the Olympic Mountains, Washington, as part of the International Geophysical Year (1956–1957) (LaChapelle, 1962). The USGS subsequently began monitoring mass balance at Wolverine and Gulkana glaciers in Alaska in 1965 as part of the International Hydrological Decade (IHD) (Meier *et al*., 1971). Mass balance has also been measured at a suite of glaciers in the North Cascades since 1984 (Pelto and Riedel, 2001).

In Canada, mass balance studies began in 1965, also in conjunction with the IHD. A west–east transect of glaciers through the southern Canadian Cordillera was chosen to study how the link between climate and glacier mass balance changes from maritime (Place, Sentinel) through transitional interior (Woolsey) to continental (Peyto, Ram River) environments (Østrem, 1966). Berendon Glacier in the northern Coast Mountains was added to form a north–south link. Of these glaciers, only Place and Peyto have been monitored continuously since 1965. Figure 2 presents time series of net balance for a selection of long-term mass balance sites.

Variability of net mass balance of maritime glaciers is most strongly controlled by winter precipitation (Hodge *et al*., 1998; Bitz and Battisti, 1999). In addition to the direct influence of precipitation on accumulation, winter precipitation can influence summer ablation: years with high winter accumulation tend to have snow cover lasting late into the summer, which maintains a high albedo relative to glacier ice and firn and reduces melt (Young, 1981; Moore and Demuth, 2001). Despite this physically based linkage, a negative correlation between summer and winter balance has not been found at all glaciers; for example, Rasmussen and Conway (2001) computed $r = 0{\cdot}16$ for South Cascade Glacier for the period 1959–1998. In continental settings, summer weather can be as strong an influence on the inter-annual variability of net balance as winter precipitation (Letréguilly, 1988; Bitz and Battisti, 1999). Summers dominated by high-pressure systems and weak regional winds typically produce high rates of ablation (Yarnal, 1984; Shea and Marshall, 2007).

In southern BC and the US PNW, there is a tendency for enhanced winter accumulation when the PNA is in a negative phase or when ENSO or PDO are in the cold phases, while reduced accumulation is associated with the enhanced phase of PNA and the ENSO and PDO warm phases (Bitz and Battisti, 1999; Watson *et al*., 2006). For example, mean winter balance at Peyto Glacier averaged 1·51 m water equivalent (we) per year from 1965 to 1976 but decreased to 1·01 m we year^{-1} over the 1977–1999 interval following the 1976 Pacific climate shift (Watson and Luckman, 2004); similar decreases occurred at other glaciers in southern BC and the US PNW (McCabe and Fountain, 1995; Moore and Demuth, 2001) (Figure 2).

Moving northward to northern BC, the Yukon and Alaska, the links between glacier mass balance and Pacific climate modes appear to weaken and in some instances exhibit a reversed polarity. For example, the 1976–1977 Pacific climate shift resulted in more negative mass balance in southern BC and the US PNW, but produced a shift to positive net balance for Wolverine Glacier in southern Alaska until 1989, when it shifted back to negative (Hodge *et al*., 1998). Josberger *et al*. (2007) suggested that the recent synchronization of negative net balance between southern Alaska and the US PNW may indicate that the winter PDO signal is being overwhelmed by a general warming trend, particularly in relation to summer balance, which appeared to become more negative following the late-1980s shift in North Pacific SSTs (Hare and Mantua, 2000; Rasmussen and Conway, 2004). Another possibility is that the more northerly glaciers are influenced by the AO, which shifted from dominantly neutral/negative to positive modes in the late 1980s (e.g. Figure 9 in Thompson *et al*., 2000). McCabe *et al*. (2000) identified a correlation between the AO and winter balance for Eurasian glaciers, but not for glaciers in western North America. We are unaware of any studies of linkages between AO and summer balance in western North America. However, Fleming *et al*. (2006) found that the positive phase of AO was associated with higher spring-summer air temperatures in northwest BC and southwest Yukon, higher spring-summer streamflow in glacier-fed catchments and an earlier freshet in nonglacier-fed catchments. These results suggest that the positive phase of AO is associated with an earlier onset of melt, which could contribute to more negative summer balances.

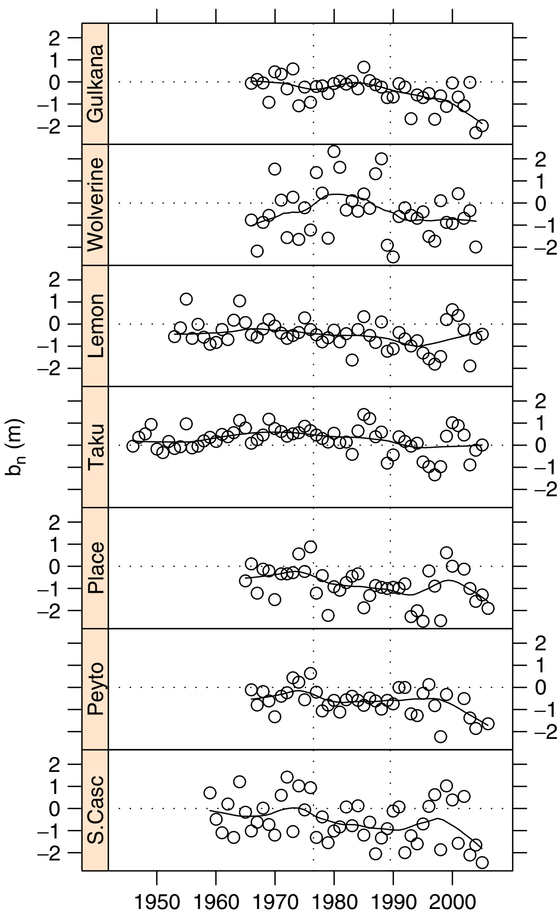

Figure 2. Annual net balance for long-term mass balance sites in western North America. Locally weighted scatterplot smoothers (LOESS curves) have been fitted to the measured values. The vertical lines indicate the PDO shift that occurred in 1976–1977 and the more recent Pacific climate shift in 1989

Unfortunately, there are insufficient long-term mass balance sites to characterize in detail the spatial pattern of mass balance teleconnections to large-scale climate patterns. However, the existence of north–south contrasts in mass balance responses to climate modes is consistent with the existence of contrasting teleconnection patterns for winter precipitation between south coastal BC in relation to north coastal BC and SE Alaska, with a 'hinge point' of zero response roughly in the vicinity of northern Vancouver Island (Fleming and Whitfield, 2006; Rodenhuis *et al*., 2007). In addition, while the 1976–1977 Pacific climate shift produced a marked decline in end-of-winter snow accumulation in the southern half of BC, this decline was more weakly expressed in the north and northeast of BC (Moore and McKendry, 1996).

Reconstructions of glacier mass balance provide a longer-term perspective on mass balance variations in southwest BC and the US PNW. These reconstructions have employed climate-based models (Tangborn, 1980; Moore and Demuth, 2001) and dendro-climatic methods (Lewis and Smith, 2004; Watson and Luckman, 2004; Larocque and Smith, 2005). In both types of reconstruction, net balance was dominantly negative throughout the twentieth century, with periods of near-neutral or slightly positive mass balance between the 1950s and the mid-1970s. However, the reconstructions may be biased because the statistical models are conditioned by the contemporary glacier geometry and do not account for past changes in glacier area and surface elevations (Elsberg *et al*., 2001). In earlier years of the twentieth century, the glacier tongue would have extended to lower elevations, likely producing a larger ablation area for a given end-of-summer snowline than would be the case for the current geometry. Therefore, the mass balance for the actual glacier geometry could have been less positive or more negative than that indicated by the reconstruction.

Changes in glacier extent and volume

Decadal and century scale changes in climate ultimately translate into variations in glacier length, area and thickness. Since the LIA, there has been marked glacier

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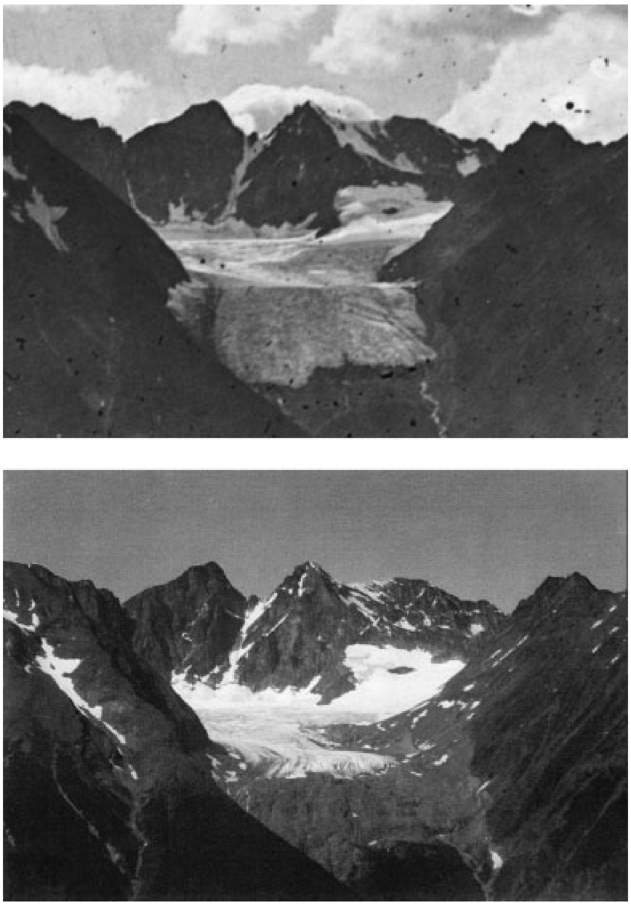

Figure 3. Photographs showing retreat of Hudson Bay Glacier, 1915 (a) to 2000 (b). Hudson Bay Glacier is located in the Coast Mountains at about 54·7 °N 127·3 °W. Figure credits: (a) G. Killam; (b) W. David

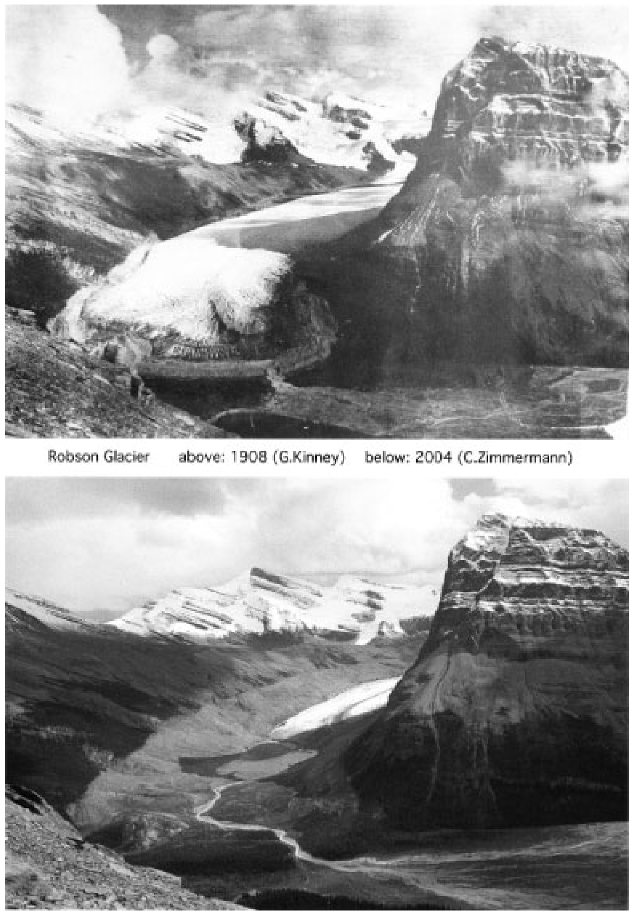

Figure 4. Photographs showing retreat of Robson Glacier, 1908 (a) to 2004 (b). Robson Glacier is located in the Rocky Mountains at about 53·2 °N 119·2 °W

retreat throughout western North America (Figures 3 and 4). While area and volume change are most pertinent for hydrology, variations in glacier length provide the oldest and most continuous records of glacier fluctuations in western Canada. Many glaciers in the Canadian Rocky Mountains retreated between 1 and 2 km since 1900 (Ommanney, 2002). Athabasca Glacier, for example retreated only 200 m between 1844 and 1906, but then receded over 1 km over the next 75 years (Luckman *et al.*, 1999). Records kept by the National Hydrological Research Institute (NHRI) for Helm and Illecillewaet glaciers, respectively, located in the southern Coast Mountains and Columbia Mountains of BC, similarly indicate about 200-m retreat until 1900, followed by retreat of 1·1 and 1·3 km, respectively, by 1995. Recession rates varied from 20 to 40 m year^{-1} between 1900 and 1960, but then slowed to an average 6 m year^{-1} between 1960 and 1980 (Osborn and Luckman, 1988), coincident with the negative phase of the PDO. Similarly, the terminus of Illecillewaet Glacier remained stationary from 1960 until 1972, and then advanced until 1990. Luckman *et al.* (1987) found that the majority of glaciers in the Premier Range advanced or were stable between 1973 and 1976. Consistent with the results from western Canada, most Alaskan glaciers studied by Arendt *et al.* (2002) retreated at rates of up to 100 m year^{-1} or more in the latter half of the twentieth century. However, the correlation between retreat rate and volume change was weak: some glaciers thickened while retreating and others thinned while advancing

Glacierized area in BC and Alberta was first calculated by Henoch (1967) at 38 613 km^2 by digitizing 1 : 1 000 000 maps (Ommanney, 2002). A more recent inventory has been completed using a combination of BC provincial 1 : 20 000 mapping based on aerial photography from 1981 to 1989, and extents for Alberta from the National Topographic Database (NTDB) at 1 : 50 000, yielding a total glacierized area of 29 830 km^2 (Menounos *et al.*, 2008). This apparent glacier loss of 22·6% should be considered with caution, given the differences in mapping scale, and the intervening decades which coincided with cooler conditions relative to those before and after. Comprehensive glacier extents have since been compiled from Landsat satellite imagery for 2005; these indicate an average area loss of 11·5% between 1985 and 2005 or $0·57 \pm 0·2\%$ per annum (Bolch *et al.*, 2008). Annual rates of area loss vary regionally from $0·35 \pm 0·1\%$ in the Northern Coast and St Elias mountains to $1·19 \pm 0·3\%$ in the Northern Interior. The southern Coast Mountains, Southern Interior and Northern Rockies have intermediate values between 0·5 and 1% per year (Bolch *et al.*, 2008). DeBeer and Sharp

(2007) compared glacier extents using satellite imagery for 2001/2002 and aerial photography from the 1950s and 1960s between latitudes 50 and 51°N. They determined area losses of 5% for the Coast Mountains (1965–2002) and 5% and 15%, respectively, for the Columbia and Rocky Mountains (1951–2001).

Overall, these area losses are less than those documented in the Swiss Alps, which have experienced 22% loss over a 25-year period to 2000 and 14% ice loss per decade since 1985, extrapolated from inventories in 1973 and 1999 (Kääb *et al.*, 2002). Alpine glaciers lost 35% of their total area from 1850 until the 1970s, and almost 50% by 2000 (Zemp *et al.*, 2006).

Schiefer *et al.* (2007) calculated glacier volume changes in BC by comparing the provincial TRIM Digital Elevation Model, which was derived by photogrammetry from the mid-1980s, with the satellite-derived Shuttle Radar Topographic Mission (SRTM) data from February 2000. The estimated total ice loss for an average 15-year period was $22{\cdot}48 \pm 5{\cdot}53$ km^3 a^{-1}, with volume loss generally proportional to regional ice area; annual thinning rates ranged between 0·53 to $0{\cdot}89 \pm 0{\cdot}18$ m a^{-1}, averaging $0{\cdot}78 \pm 0{\cdot}19$ m a^{-1} over the province. Regionally, thinning rates are highest in the North and South Coast and St Elias mountains, where glacier areas are the most substantial (~21 500 km^2 or 75% of all BC glaciers), and also in the Central Rocky Mountains (350 km^2), and are lowest in the Columbia/Interior and Northern Rocky mountains (3500 km^2). The volume loss was accompanied by strong terminus retreat except in northwest BC, where there was less marked retreat. The greatest uncertainty in thickness change occurs in accumulation zones of large glaciers and snowfields that lack contrast in the original photographs used to produce the TRIM DEM. Higher rates occur locally, especially in the ablation areas, while considerably lower rates were noted for earlier periods comparing NTDB data with TRIM for change in the cooler 1960s and 1970s. Consistent with the results for BC, Larsen *et al.* (2007) documented surface lowering over 95% of the glacier area they studied in southeast Alaska and northwest BC over the last few decades.

In comparison to the Canadian Cordillera and southern Alaska, glaciers cover a considerably smaller percentage of mountainous terrain in the conterminous United States. At the end of the twentieth century, glaciers covered about 688 km^2 (Fountain *et al.*, 2006), restricted to mountain ranges within the states of Washington, Oregon, California, Nevada, Idaho, Montana, Wyoming and Colorado (Krimmel *et al.*, 2002) (Figure 1). About 65% of the glacierized terrain is located in Washington (Fountain *et al.*, 2007). Like the glaciers in the Canadian Cordillera, the glaciers of the American West receded greatly since the LIA through to the middle of the twentieth century, pausing or advancing before resuming accelerated retreat in the late-twentieth century and continuing into the twenty-first century (Phillips, 1938; Hubley, 1956; LaChapelle, 1960; Krimmel *et al.*, 2002; Hoffman *et al.*, 2007; Jackson and Fountain, 2007). For example, at Mount Baker, glacier termini retreated rapidly until about 1950, when they began to readvance during the following two decades of cool and wet conditions (Harper, 1993; Kovanen, 2002). During the period 1950–1980, Roosevelt and Easton glaciers advanced about 600 m (Kovanen, 2002). Both glaciers began retreating in the 1980s. Broadly similar behaviour was observed in Glacier National Park, Montana (Hall and Fagre, 2003), in the Oregon Cascades (Jackson and Fountain, 2007), and in the Colorado Front Range (Hoffman *et al.*, 2007).

Glacier area in the North Cascades declined by 7% between 1958 and 1998 (Granshaw and Fountain, 2006). The majority of this loss occurred at the lowest elevations, where increases in air temperature had the most effect. On the basis of an area–volume scaling relation (Bahr *et al.*, 1997), glaciers lost $0{\cdot}8 \pm 0{\cdot}1$ km^3 of ice, and this loss accounts for *ca* 6% of regional streamflow during the months of August and September (Granshaw and Fountain, 2006). Over the same period glacier area decreased about 40% in Glacier National Park, Montana (Hall and Fagre, 2003) and 20% in Oregon (Jackson and Fountain, 2007). In the Colorado Front Range the areal shrinkage was near zero for some glaciers and for others 30% (Hoffman *et al.*, 2007). The small cirque glaciers of Colorado differ in many respects from glaciers elsewhere in western North America because they are small (average size of 3·38 ha) and do not have distinct accumulation and ablation zones, and a sizable fraction of their nourishment is controlled by redistributed snow during the accumulation season (via wind transport and avalanches). The effects of wind transport and avalanches on snow deposition obscure the relation between snow accumulation and winter precipitation, in contrast to most other temperate glaciers. Summer temperature explains a substantial fraction of the inter-annual variability in net mass balance for these small glaciers (Hoffman *et al.*, 2007; Basagic, 2008).

Summary

The glaciers of western Canada and the conterminous United States have retreated since about the mid-nineteenth century, although rates have varied through time. The first-half of the twentieth century saw rapid retreat, followed by weaker retreat or advance until 1980, with a shift back to relatively consistent recession in the last three decades. The minor advances of glaciers in the Canadian Cordillera in the late 1960s and early 1970s (Luckman *et al.*, 1987; Osborn and Luckman, 1988) occurred during the negative phase of the PDO (*ca* 1947–1976) when winters tended to be cold and wet (Mantua *et al.*, 1997; Menounos, 2002). The dominance of negative mass balance conditions and volume loss over the last few decades indicates that glaciers throughout western North America are out of equilibrium with the current climate and, barring a shift to cooler and/or wetter conditions, will likely continue to retreat over at least the next decade or so. Some small glaciers disappeared over the last few decades and, under current climatic conditions, some additional glaciers may disappear (Hall and Fagre, 2003; Pelto, 2006). The potential effects of projected future climate change on glacier coverage and streamflow will be considered in detail in the next section.

CLIMATE–GLACIER–STREAMFLOW INTERACTIONS

Effects of glaciers on seasonal and inter-annual variability

Hot, dry conditions that generate low flows in unglacierized catchments favour high rates of glacier melt that can augment streamflow, especially during late summer and early autumn (Meier, 1969). In western North America, glacial influences are most clearly and consistently expressed in August, after most non-glacier snow has melted and before the onset of autumn cooling and the autumn–winter rainy season. Stahl and Moore (2006) found that glacial augmentation of August streamflow was apparent in catchments with as little as 2–3% glacier cover (Figure 5). This flow augmentation should be especially notable in years with low-snow accumulation, when the area of exposed low-albedo ice is high. The inter-annual variability of runoff decreases with increasing fractional glacier cover (up to about 30–40% cover) because of the mutual buffering of runoff variability between ice-free and glacierized portions of the catchment (Fountain and Tangborn, 1985; Moore, 1992; Fleming and Clarke, 2005).

Streamflow in western North America varies systematically in relation to climate modes such as ENSO and PDO due to their influence on air temperature and precipitation, particularly in winter (e.g. Cayan and Peterson, 1989; Kahya and Dracup, 1993; Lall and Mann, 1995; Woo and Thorne, 2003; Fleming and Quilty, 2006; Fleming *et al.*, 2007). The presence of glaciers can have a strong influence on these climate–streamflow links. For example, Neal *et al.* (2002) found that the 1976–1977 PDO shift affected the seasonal distribution of flows for six streams in SE Alaska, with contrasting responses between the strongly glacier-fed Mendenhall River and five snowmelt-dominated streams. For snowmelt-dominated streams, winter flows increased and summer flows decreased following the shift to the PDO warm phase, due to the increase in the fraction of winter precipitation falling as rain and therefore becoming streamflow in winter rather than being released later as snowmelt. For the Mendenhall River, however, higher flows were observed for all seasons during the post-shift warm phase PDO conditions, particularly following 1989. Neal *et al.* (2002) ascribed these higher summer flows to an increase in glacier melt during warm phase years, but did not examine mass balance data. As seen in Figure 2, mass balance for the nearest glacier (Lemon Creek) did tend to be more negative following 1976, and particularly between 1989 and 1998.

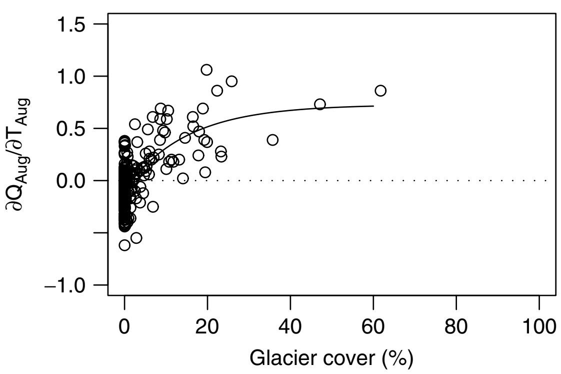

Figure 5. Sensitivity of August streamflow to August air temperature as a function of glacier cover (after Stahl and Moore, 2006). The sensitivity was computed for each hydrometric station by fitting a multiple regression model for August streamflow with July streamflow, August air temperature and August precipitation as predictor variables. All variables were standardized prior to fitting the regression, so the sensitivity is dimensionless

Loosely similar responses have been found in relation to the effects of the AO and ENSO. In southwest Yukon and northwest BC, positive AO years appear to be associated with warmer spring–summer conditions, leading to an earlier freshet in nival rivers with little change in the annual mean flow, but higher melt production in glacial rivers yielding overall yearly flow increases (Fleming *et al.*, 2006). In the Alberta Rockies, the 1997–1998 El Niño event produced increased flow in a glacier-fed river and decreased flow in a nearby nival river as a result of the low snow accumulation in that year and the enhanced glacier melt resulting from early snow disappearance (Lafrenière and Sharp, 2003).

These effects of glacier cover on streamflow response to climate modes are consistent with our understanding of the differential responses of glaciers and non-glacier land cover to variations in winter snow accumulation and summer temperature (the latter being an index for the energy available for melt). However, no studies appear to have addressed how changes in glacier state through time influence the effects of climate modes on streamflow.

Historic influence of glacier changes

Hock *et al.* (2005) outlined the processes by which mountain glacier discharge responds to climate warming and a shift from near-neutral to negative mass balance. They distinguished between a short-term response to changes in climate and the extents of snow and firn, and a long-term response, which includes the change in glacier area within the catchment. The short-term response to higher temperatures is characterized by enhanced meltwater production due to the earlier disappearance of high-albedo snow. In addition, the reduction in the firn area and thickness, and greater exposure of bare ice, allow not only greater melt, but also more rapid water flow over the glacier surface. The combination of these changes generates higher peak flows and greater diurnal variation. During this short-term response, glacier mass loss would in many cases be dominated by thinning with little to no terminus retreat. However, sustained conditions favouring negative mass balance will eventually result in glacier retreat, a reduction in the area available for meltwater

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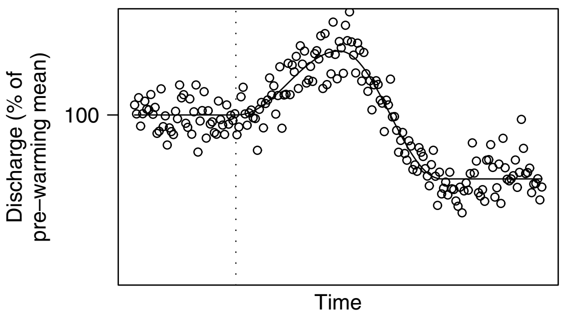

Figure 6. Hypothesized streamflow response to the onset of a climatic warming trend. The discharge and time scales are unspecified on purpose, reflecting uncertainties associated with both fundamental knowledge gaps and variability in response times and magnitudes among glaciers. The vertical line indicates the onset of warming. For simplicity, the trend line indicates an eventual stabilization of the streamflow regime

production, and a declining trend in streamflow that would persist until the glaciers either achieve a new equilibrium geometry or disappear (Figure 6).

Several studies analysed streamflow trends in glacier-fed catchments. Moore and Demuth (2001) could not detect significant trends in August streamflow for a station immediately below Place Glacier in southwest BC. However, a negative trend was found after statistically adjusting August flows for the effects of August temperature and winter mass balance. These results are consistent with the hypothesis that, after accounting for factors that control melt intensity, discharge should decrease for basins where glaciers are retreating. Fleming and Clarke (2003) found that recent warming in southwest Yukon and northwest BC was associated with a negative trend in annual flow for unglacierized catchments, but a positive trend in river flow was observed for glacierized catchments. Like Moore and Demuth (2001), Stahl and Moore (2006) examined August rather than annual streamflow to minimize confounding influences of snow accumulation and rainfall, and thus better isolate the effects of glacier melt. They also tested for trends both before and after adjusting for variables including August air temperature and precipitation. Unglacierized catchments exhibited inconsistent trends for both the raw and the adjusted data, while glacierized catchments showed consistent, statistically significant decreases for both raw and adjusted data, except in northwest BC. In that region, some positive trends in August streamflow were found for glacierized catchments, consistent with the results of Fleming and Clarke (2003).

This geographic contrast in trends may result from the fact that glacier volume loss in most of BC was accompanied by substantial terminal retreat and a reduction in glacier area except in the northwest, where mass loss occurred mainly by thinning with less areal decrease (Schiefer *et al.*, 2007; Bolch *et al.*, 2008). Therefore, it appears that the initial phase of streamflow response to warming has passed over much of the study region, but that northwest BC and southwest Yukon are still experiencing the initial phase. The latter situation also appears loosely consistent with the colder (subarctic) conditions of the area, and in particular, the fact that many glaciers in the BC–Yukon–Alaska border region are effectively lobes of the St Elias icefield, the largest body of ice outside Greenland and Antarctica. Thus, the historical streamflow responses of glacial rivers in that region may be reminiscent of the meltwater pulses that accompanied waning of Pleistocene ice sheets (indeed, some ecological studies have used the region as a contemporary analogue to post-glacial species recolonization), and the contrast in streamflow responses between this region and those further south may constitute a large-scale space-for-time substitution. Clearly, however, further research is necessary to document and explain in detail the role of glaciers in these geographically contrasting trends.

Unstable glacial lakes may be formed by ice dams (moraine-dammed glacial lakes are discussed separately in relation to geomorphologic hazards). Ice dam failures yield glacial outburst floods, or jökulhaups. Such floods can occur frequently in some catchments, and indeed occur annually at some sites in northwest BC, southwest Yukon and southeast Alaska. The fundamental physics of glacial outburst flood generation and models for routing the resulting flood waves were outlined decades ago (Clarke, 1982; Fernández *et al.*, 1991). However, in spite of much ongoing research on large Icelandic jökulhaups and Pleistocene outburst megafloods, little work appears to have been devoted to assessing the potential impacts of climate variability and change upon outburst floods for contemporary mountain glaciers. One South American study found a linkage to ENSO for an Andean glacier-dammed river (Depetris and Pasquini, 2000), suggesting that this line of investigation may be fruitful. Although most of the locations in North America where such phenomena regularly occur are remote and sparsely populated, these regions are of growing interest to the tourism and mining industries. The potential for climate-driven changes in jökulhaup frequency, timing, and magnitude therefore presents concerns for human safety and engineering design, and warrants further research effort.

Potential effects of future glacier change on streamflow

The dominant approach to assessing the hydrologic response to future climate scenarios is to calibrate a hydrological model to current conditions, then run it using climate forcing representing a projected future climate state. Two general techniques are commonly used to derive climate scenarios for this purpose: (i) the delta-change approach, in which a prescribed change, usually inferred from before-and-after general GCM runs, is applied to historical time series of precipitation and temperature, and (ii) statistical downscaling of output from coarse-gridded GCMs to represent conditions at the location of interest. Dynamically downscaled climate projections from regional climate models do not yet appear to have been used to derive future climate scenarios for specifically assessing impacts to glacier-fed rivers.

Streamflow response to future climate scenarios has been modelled for glacier-fed catchments in the European Alps, Scandinavia, Iceland, the Himalayas and

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the Andes (Braun *et al.*, 1999; Hagg *et al.*, 2006; Horton *et al.*, 2006; Rees and Collins, 2006; Singh *et al.*, 2006; Einarsson *et al.*, 2007; Hubbard *et al.*, 2007; Huss *et al.*, 2008; Juen *et al.*, 2007). In western North America, Moore (1992) applied delta-change scenarios to a model for the Lillooet River in southwest BC, which has approximately 15% glacier cover. However, he did not adjust the glacier cover, which limits the inferences to short-term responses. Loukas *et al.* (2002a,b) also used the delta-change approach to assess streamflow changes between climate scenarios representing 1970–1990 and 2080–2100 for the Illecillewaet River in the Columbia Mountains of BC. They reduced glacier area by one-third for the future climate scenario to account for glacier retreat, but did not explain how they arrived at this figure. Figure 5 in Loukas *et al.* (2002a) suggests a slight increase in glacier melt contributions to streamflow in May and June (presumably due to earlier disappearance of snow cover), a decrease from July to September (likely due to the decreased area of ice available for melt) and little change in October.

Stahl *et al.* (2008) applied downscaled climate scenarios to drive a model for the Bridge River, located north of the Lillooet catchment, into the future. They introduced a glacier response routine based on volume–area scaling, which has been used in glaciological studies and regional climate modelling and can be a robust estimator of transient glacier change (Radic *et al.*, 2007). The model output indicates that glacier area in the Bridge River catchment will decline even under a steady-climate scenario, with the glacier retreating to a new equilibrium within 100 years, ultimately losing about 30% of its current area. This loss of glacier cover would be accompanied by a similar decline in summer streamflow. For climate scenarios based on the IPCC B1 and A2 scenarios, glacier retreat would continue with no evidence of reaching a new equilibrium over the next century. Figure 7 shows monthly streamflow for the observed record and for the end of this century as modelled with climate forcing of the A2 scenario downscaled from the Canadian Climate Model runs. The dramatic decrease in glacier area results in decreased streamflow throughout the melt season. Stahl *et al.* (2008) found that uncertainties in model parameters and in downscaling climate time series propagate into considerable uncertainty in future glacier retreat and streamflow response, and stressed the utility of glacier mass balance data for constraining model calibration to ensure proper simulation of both streamflow and glacier response to climate forcing.

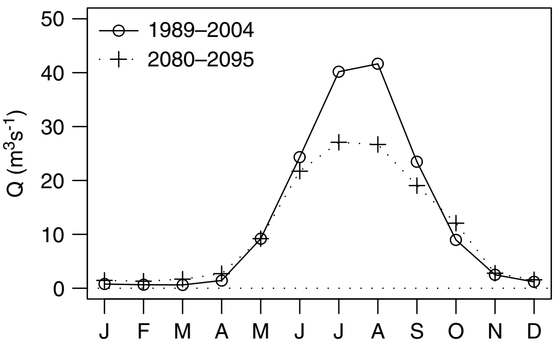

Figure 7. Mean monthly streamflow for Bridge River, comparing measured flows for 1989–2004 (glacier cover 61%) to projected flows for 2080–2095 for the IPCC SRES A2 emissions scenario (glacier cover about 30%). On the basis of results reported by Stahl *et al.* (2008)

GEOMORPHIC PROCESSES AND HAZARDS

Introduction

Climatic warming and associated glacial retreat during the twentieth and early twenty-first centuries have been cited as causative factors for a variety of landslide and flood hazards in alpine basins (Bovis, 1990; Evans and Clague, 1994; Abele, 1997; Berrisford and Matthews, 1997; Haeberli *et al.*, 1997; Ryder, 1998; Holm *et al.*, 2004; Mortara *et al.*, 2005; McKillop and Clague, 2007). Glacier retreat can debuttress bedrock slopes, deposit glacigenic sediments in areas prone to instability, create lakes impounded by unstable moraines which can later fail, and deposit sediment in locations prone to erosion and entrainment by other landslide processes. This section reviews the effect of glacier retreat on geomorphic processes and hazards; their implications for fluvial suspended sediment concentrations are discussed in a later section on water quality.

Hazard types

Geomorphic hazards associated with glacial change include rock avalanches, deep-seated slope sagging, debris flows, debris avalanches, debris slides, rock fall, moraine dam failures and glacier outburst floods (Figure 8).

Many rock avalanches have been documented in close proximity to glaciers, including at least 16 historic events within the Canadian Cordillera (Evans and Clague, 1988, 1994; Geertsema *et al.*, 2006). Most events occurred in remote locations and did not affect humans, although two events in 1978 and 1999 at Telkwa Pass, BC, reached the valley bottom where they ruptured a natural gas pipeline (Schwab *et al.*, 2003).

In the Coast Mountains there are several documented instances of deep-seated sagging (sackung) features in areas where recent ice retreat has removed buttress support to glacially undercut slopes (Bovis, 1982, 1990; Evans and Clague, 1994; Bovis and Evans, 1996; Bovis and Stewart, 1998). Bovis (1982) identified ongoing slope sagging above Affliction Glacier, BC, which has undergone at least 100 m of downwasting in the last 150 years (Figure 9). Evans and Clague (1994) described extensive sackung development above Melbern Glacier, St Elias Mountains, BC, following glacial thinning of 400–600 m over the past 200 years. Holm *et al.* (2004) documented eight locations where deep-seated sagging occurs above glacial oversteepened slopes containing large ($>10^4$ m^3)

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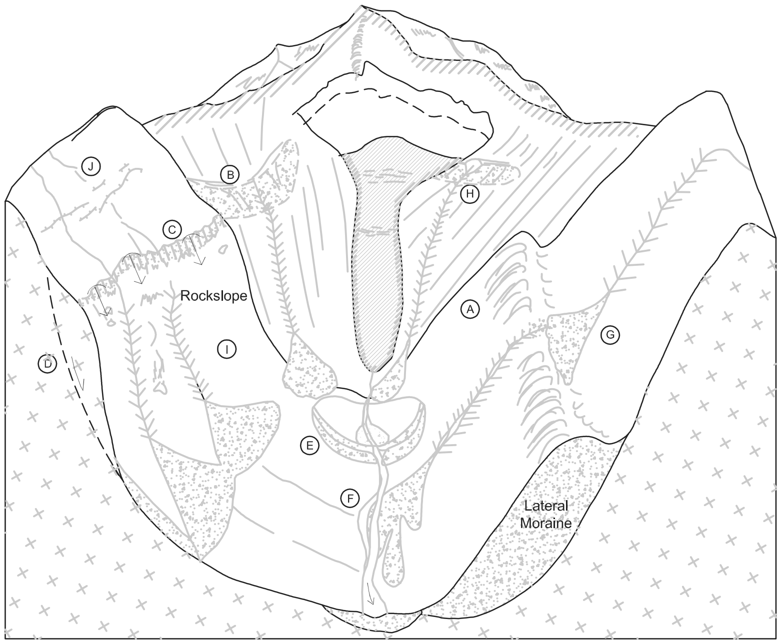

Figure 8. Block diagram showing geomorphic hazards associated with glacier retreat. (A) Moraine sediment entrained by failure upslope, (B) End-moraine in hanging valley acting as a sediment source, (C) Increased spatial frequency of rockfall along convex slope break formed by glacial trimline, (D) Rockslide initiation on glacially debuttressed slope, (E) Moraine dam outbreak flood, (F) Landslide dam outbreak flood, (G) Partial capture of debris by lateral moraine trough, (H) Debris avalanche—flow initiating in cohesive sediment debuttressed by glacial thinning, (I) Reduction in rockfall frequency in locations 'cleaned' by glacial scour, (J) Sackung (slope sagging) features above glacially debuttressed slope

Figure 9. Slope sagging, Affliction Glacier, British Columbia

rockslope failures. Their coexistence suggests an association between large rockslope failures, gravitational slope deformation and glacially oversteepened slopes.

Large debris flows and debris avalanches also take place in areas recently exposed by glacier retreat, including the Canadian Rocky Mountains (Jackson *et al*., 1989) and the southern Coast Mountains. Near Mount Meager, for example, Bovis and Jakob (2000) documented a $1{\cdot}2 \times 10^6$ m^3 debris flow in 1999 at Capricorn Creek, BC, which travelled 4 km and dammed Meager Creek for several months. The debris flow resulted from failure of glacially debuttressed colluvium overlying weak volcaniclastic material in a location that was ice covered some 100–150 years ago (Figure 10).

As glaciers recede, moraine-dammed lakes can form. Failure of moraine-dammed lakes in western North America occurs rarely but with sufficient destructive potential to warrant assessment where such lakes exist above existing or proposed development (Blown and Church, 1985; Clague and Evans, 2000; O'Connor *et al*., 2001). In low-gradient streams, these events generate water floods, but debris floods and flows may occur in steeper, sediment-filled stream reaches. The magnitude of downstream flows during lake outbursts depends on the initial volume of water stored in the lake and the mode of dam breaching, which will govern the duration over which the water is released. McKillop and Clague (2007) documented 174 moraine-dammed lakes in the southern

Figure 10. Debris avalanche, Capricorn Creek, British Columbia

Coast Mountains of BC, and described a method to evaluate outburst flood hazard likelihood and magnitude.

Influences on geomorphic hazard activity

The frequency, magnitude, and type of geomorphic hazards in areas subject to glacier retreat vary strongly because recent glacial change is only one of many factors influencing landslide activity in alpine basins. Other factors include the effects of pre-Holocene glacial erosional episodes, controls exerted by rock structure and lithology, variations in geotechnical characteristics of sediment, and undercutting of slopes by fluvial erosion.

Holm *et al.* (2004) identified several factors that influence the relation between landslide activity and recent glacier retreat. In bedrock, landslide activity varies appreciably with rock mass strength, orientation of bedrock discontinuities with respect to the hillslope orientation, and the extent of glacial scour below the LIA glacial trimline. Valleys eroded in weak rock masses such as Quaternary volcanics are oversteepened and contain more deep-seated slope movement features. These valleys also contain many rockfalls, rock slides, and rock avalanches near glacial trimlines. The relation between bedrock instability and glacier retreat in basins underlain by stronger rock masses, such as granitic intrusives, is weak. However, shallow-seated rock slides along trimlines and failures do occur in basins underlain by resistant bedrock in locations already prone to instability, such as in steeply dipping rock masses where the dominant joint set daylights as glaciers recede.

In both types of bedrock, instability often occurs upslope of the LIA glacial trimline. In surficial material, landslides associated with post-LIA retreat initiate primarily as debris avalanches transforming into debris flows, concentrated along lateral moraines or glacial trimlines. Glacial deposits may also increase the magnitude of failures that initiate upslope through entrainment of deposits within the transportation zone.

McKillop and Clague (2007) suggested that outburst flood hazards are greatest for moderately large lakes that are impounded by large, narrow, ice-free moraine dams, where the dam is composed of sedimentary rock debris and is drained by a steep, sediment-filled gully. Under these conditions the outburst flood is most likely to trigger a debris flow with the potential to enlarge downstream through further entrainment of gully material.

Glacier retreat or downwasting does not always translate into high rates of mass wasting. For example, recent work on the Cheekye River catchment in BC demonstrated that glacial retreat in the uppermost basin likely reduced the potential for large runout debris flows that may evolve from rock avalanches (BGC, 2007). In this case, glacial retreat removed the largest potential source for water entrainment during a rock avalanche, and water sources are now limited to rainfall and snowmelt. This situation contrasts with debris flows from other Quaternary volcanoes in the PNW such as Mount Rainier, Mood Hood or Mount Baker, where heavily glaciated terrain represents potential sources for water entrainment by rock avalanches (Iverson, 1997).

Future implications

Future glacier retreat in the Western Cordillera will expose new areas subject to a geomorphic hazard response. Whether this retreat results in increases, decreases, or little change in hazard activity (frequency or magnitude) depends strongly on individual catchment characteristics; generalizations between basins are thus fraught with uncertainty. Nonetheless, ongoing glacier retreat has the potential to change geomorphic hazard levels in some basins, and must be considered when completing a geohazard assessment for proposed or existing development in these areas. In many cases, erosional processes may deliver significant quantities of sediment to stream channels, with implications for channel morphology (in the case of coarse sediment) and water quality (for fine sediment).

WATER QUALITY

Unlike the case for streamflow, records of water quality in western North America are generally too short to allow time-series analysis of the effects of historic glacier change. In this section, an attempt is made to use space-for-time substitutions and reasoning based on process knowledge to draw tentative inferences about the potential effect of future glacier retreat on water-quality parameters, including chemistry, temperature and suspended sediment concentrations.

Water chemistry

Glacier meltwaters initially tend to be relatively dilute, and most solutes exported from glaciers are acquired by water following subglacial flowpaths (Richards *et al.*, 1996). Firn and ice tend to be more dilute than snow due to the leaching of snowpack ions during melt (Fountain, 1996). As glaciers retreat, several processes may influence the chemistry of water exiting a glacier, including shifts in the relative importance of sub-, en- and supraglacial flowpaths.

Areas exposed by deglaciation are subjected to fundamentally different weathering processes compared to those in the subglacial environment, resulting in a shift in chemical species and concentrations in water draining from these areas relative to glacier discharge (Anderson *et al.*, 1997). Following deglaciation, weathering rates and processes in glacier forefields continue to evolve, especially with establishment of vegetation and ongoing soil development (Anderson *et al.*, 2000). At a given point along a stream, water chemistry will depend not only on the chemical characteristics of the water sources, but also the rates of contribution from each source and the effects of in-stream processing. Given this complex array of processes, many of which likely exhibit transient behaviours and a strong dependence on local conditions (Anderson, 2007), it is difficult to predict *a priori* how streamwater chemistry will respond to glacier retreat. As an example of the biogeochemical changes that are associated with glacier changes, Filippelli *et al.* (2006) used chemical analysis of lake sediment cores to show that the dominant forms of phosphorus exported from a catchment can shift from mineral P to occluded and organic forms following deglaciation.

Spatial comparisons of water chemistry suggest that higher glacier cover tends to be associated with more dilute streamwater, at least during the melt season. For example, Hood and Scott (2007) monitored six adjacent catchments in southeast Alaska, and found that the physical and chemical properties of streamwater did not vary with catchment glacier cover during winter. However, during summer, nutrient concentrations were negatively correlated with glacier cover. Lafrenière and Sharp (2005) similarly found higher solute concentrations in a stream draining an unglacierized catchment in the Alberta Rockies despite the presence of more resistant lithology in that basin, likely due to the presence of better developed soils and greater contact times. Lafrenière and Sharp (2005) also found that proglacial chemical concentrations were lower during an El Niño year because the higher discharge that year was associated with a change in water routing, leading to lower contact times with the glacier bed. The nonglacier-fed stream, on the other hand, experienced higher concentrations during the El Niño year, which was associated with lower runoff.

In areas that have airsheds influenced by agricultural and industrial areas, there is potential for the accumulation of volatile organic compounds (VOCs) in glacier snow, firn and ice (Blais *et al.*, 2001; Lafrenière *et al.*, 2006). Enhanced export of VOCs from glacierized catchments results from the early channelization of flow (with limited prior contact with soils or sediments), coupled with the low organic content of sediments in these catchments. These factors limit the opportunity for VOCs to be removed from runoff by sorption to organic matter. An increase in melt associated with El Niño conditions or climate warming could produce more intense pulses of VOCs into receiving waters below the glaciers, with possible consequences for aquatic organisms.

Another potential water-quality effect of glacier retreat and longer-term decline in streamflow is a reduction in the capacity of streams to dilute pollutants such as industrial effluent and non-point source contaminants such as agri-chemicals.

Stream temperature

Stream temperature patterns reflect the complex interactions of hydrologic and microclimatic processes. Water leaving a glacier will be close to 0 °C. In spring, these near-freezing water temperatures are typical of all the snow-fed streams in high alpine zones. As summer progresses, however, non-glacial streams warm as the contributing seasonal snowpack diminishes and disappears while the glacier-fed streams remain cold. The degree to which glaciers affect downstream water temperatures depends in part on the glacier area, distance downstream, climate and flow conditions and the flux of non-glacial water to the streams (Brown *et al.*, 2006).

Both physically based modelling and empirical studies have demonstrated that stream temperature is positively correlated with air temperature (as an index of heat exchange, particularly solar radiation) and negatively with discharge (e.g. Hockey *et al.*, 1982; Gu *et al.*, 1998). Given that glacier melt tends to increase streamflow during periods of high air temperature, glaciers should regulate the thermal regime of streams and help maintain low stream temperatures during periods when nonglacier-fed streams may warm significantly. On the basis of the above arguments, streamflow declines associated with glacier retreat should generate higher stream temperatures, particularly if summer weather becomes hotter and drier in the future.

Another influence of glacier retreat is the formation of proglacial lakes. In non-glacial settings, lakes can have a profound influence on stream thermal patterns (e.g. Mellina *et al.*, 2002). However, thermal processes in proglacial lakes are likely distinct to those in non-glacial settings due to low residence times (i.e. low ratios of storage to inflow) and the influence of suspended sediment concentration on water density and thus vertical mixing (Weirich, 1985, 1986). Weirich (1986) found that a small proglacial lake in southeastern BC was dominantly isothermal. In contrast, Richards (2008) documented complex and dynamic vertical temperature profiles in proglacial Place Lake in the BC Coast Mountains, and found that outflow temperatures were essentially the same as mid-lake temperatures in the top 2 m. There is a need for detailed study of thermal processes in proglacial lakes to provide a basis for understanding and predicting their influence on stream temperature in the context of ongoing glacier retreat and climate warming.

Two studies used multiple regression analysis to quantify the effect of glacier cover on stream temperature in BC. Moore (2006) used spot temperatures recorded by Water Survey of Canada technologists during visits to hydrometric stations to compute median temperatures for each month. The cooling effect of glacier cover was significant in July, August and September, with a decrease of 1·2 °C for each 10% increase in glacier cover in July and August, and 0·6 °C per 10% glacier cover in September. Nelitz *et al.* (2008) compiled stream temperature data for over 400 streams in BC and calculated the maximum value of a 7-day running mean of daily average temperatures, a metric often termed the maximum weekly average temperature (MWAT). It indexes thermal suitability for fish species (Eaton *et al.*, 1995) and correlates well with biological processes for different life stages of salmonids (Sullivan *et al.*, 2000), particularly rainbow trout (Nelitz *et al.*, 2007). A multiple regression model with a linear relation between MWAT and fractional glacier coverage suggests that a decrease in glacier cover equivalent to 10% of the catchment area would be associated with a 1.6 C increase in MWAT. However, an updated analysis suggests the relation is non-linear, with increasing sensitivity with decreasing glacier cover (Moore *et al.*, unpublished).

If a space-for-time substitution is valid, the regression results suggest that temperature impacts of glacier retreat would be greatest in July and August, and particularly during the periods of hot, dry weather that generate the MWAT each year, consistent with our understanding of the governing processes. However, further research is required. Long-term monitoring programmes need to be initiated on a range of streams, both with and without glacier contributions. In addition, studies should examine stream temperature processes in glacierized regions to provide a sound basis for developing and testing stream temperature models. For example, heat exchange processes in steep streams with cascading flow may not be well described by equations commonly used to compute stream surface heat exchanges (Richards, 2008).

Suspended sediment

Suspended sediment yield generally increases with glacier cover in mountain watersheds (Harbor and Warburton, 1993; Hallet *et al.*, 1996). Conditions favouring negative mass balance and glacier retreat can produce elevated suspended sediment concentrations in proglacial streams by a variety of mechanisms, including sediment delivery via debris flows and other mass-wasting processes associated with glacier retreat, as described in the previous section. In addition, during years of strongly negative mass balance when high volumes of meltwater reach the glacier bed, subglacial sediments can be efficiently flushed (Jansson *et al.*, 2005). Rapid glacier retreat can also release sediments stored in ice near the terminus, near the bed of the glacier, as well as from recently deglaciated moraines and forefields. Sediment can reach the fluvial network through a variety of processes, including sediment detachment and entrainment by overland flow, mass wasting, or lateral erosion of streams in the glacier forefield. In a small glacierized basin in the Rocky Mountains, for example, Orwin and Smart (2004a) observed that over 80% of suspended sediment exported from the watershed originated from the glacier forefield rather than from subglacial environments. Much of this sediment originated from sources within and adjacent to the stream channel.

The importance of glacier forefields as sediment sources is transient as surface armouring (winnowing), reduction of surface slope, and colonization of surfaces by vegetation act to reduce sediment availability. All of these processes are time dependent, so areas of recently deglaciated terrain should be more effective sediment sources than older ones. Short-term monitoring of suspended sediments released from surfaces of different age confirms this hypothesis (Orwin and Smart, 2004b).

Many of the processes described above represent important components of paraglacial sedimentation, a concept that is used to explain elevated rates of mass wasting and fluvial sediment transport following glacier retreat (Church and Ryder, 1972; Ballantyne, 2002). Paraglacial effects can last for decades and centuries in small, alpine watersheds (Ballantyne, 2002; Orwin and Smart, 2004b), while some of the largest rivers in BC continue to transport high suspended sediment loads as they adjust to the tremendous volume of sediment delivered to them during the demise of the Cordilleran ice sheet (Church and Slaymaker, 1989). While paraglacial sedimentation is conceptually well understood, quantitative models for predicting its magnitude and time scale are lacking.

Other factors may act to decrease suspended sediment concentration in rivers following glacier retreat. As glaciers become smaller, for example, the area of the glacier in contact with its bed will decline, with an associated reduction in basal erosion (Hallet *et al.*, 1996). Furthermore, terminal retreat often results in formation of proglacial lakes within overdeepened bedrock basins, which can trap and store sediment discharged by a glacier, at least until the lakes fill. Smith (1981), for example, observed that Bow Lake sedimentation declined following the formation of an ice-marginal pond between the lake and its dominant sediment source: the Wapta Icefield.

Although there are few long-term monitoring records to assess how changes in glacier cover affect suspended sediment concentration, several studies have examined

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the relation between glacier cover and lake sedimentation, a proxy for suspended sediment yield. Percent ice cover and sediment yield might be expected to covary because more extensive ice increases the area subject to subglacial erosion (Hallet *et al.*, 1996). The relation between ice cover and lake sedimentation, however, is not simple since it is governed by other factors that include climate regime, and changes in sediment storage. A complex relation exists between glacierized area and sedimentation in Hector Lake, Alberta (Leonard, 1997). High sedimentation rates coincided with times when glaciers were extensive, but also during periods of rapid glacier advance and retreat. In the southern Coast Mountains, times of high lake sedimentation generally coincided with periods when glaciers rapidly retreated from downvalley positions reached during the LIA (Menounos *et al.*, 2005). In the Cheakamus and Green Lake basins, the highest sedimentation of the last 600 years occurred during the period 1920–1945 (Menounos, 2006; Menounos and Clague, 2008). Elevated sedimentation rates also occurred in proglacial lakes of the Canadian Rocky Mountains during the early twentieth century (Leonard, 1981). High sedimentation rates in the proglacial lakes imply that river-suspended sediment concentrations were elevated and coincided with a period when glaciers throughout the Canadian Cordillera underwent rapid glacier retreat.

In summary, continued glacier recession is expected to elevate concentrations of suspended sediments in many proglacial rivers at time scales of years to decades due to paraglacial sedimentation and release of sediments from subglacial sources. However, a long-term decline in suspended sediments delivered from glacial sources is anticipated under future climate change scenarios since the area of glacier cover will decrease and glacier forefields will stabilize. In some catchments, mass-wasting associated with glacier retreat (as outlined in the section on Geomorphic Hazards) could provide episodic inputs of substantial amounts of both fine and coarse sediment to downstream channels, disrupting a longer-term decline.

IMPLICATIONS FOR THE TWENTY-FIRST CENTURY

On the basis of GCM simulations, the most likely climatic scenario for the twenty-first century is for continued warming in western North America (e.g. Mote *et al.*, 2005; Rodenhuis *et al.*, 2007). While limited in number, studies have shown that this warming will likely be accompanied by continued glacier retreat over at least the next few decades (Hall and Fagre, 2003; Stahl *et al.*, 2008). While historic warming has been associated with streamflow increases in some glacier-fed catchments in the northwest portion of the study area, this trend is expected to be a transient response that will ultimately shift to a trend to declining streamflow, consistent with documented trends for most of BC. However, the time scale over which this shift will occur is unclear and requires further research. In addition to declining streamflow, glacier retreat is likely to produce a range of other changes, including higher stream temperatures, increased concentrations of organic matter and changes in the concentrations and forms of some nutrients in streamwater, and, in some cases, greater exposure to hydrogeomorphic hazards such as mass movements and outburst floods. The effect on suspended sediment concentrations is less clear and likely to depend on local conditions in the shorter term, but the longer-term trend should be a reduction. The following sections explore some of the implications of these changes in relation to water resources and aquatic ecology.

Water resources

Glacier cover can be viewed as a signal processing or filtering mechanism (Fleming and Moore, 2008) that acts on climate signals, such as long-term climatic drift or coherent modes of annual or decadal variability like ENSO, PDO, PNA and the AO; the output of the filter is streamflow. The effect of glaciers can be profound, in some cases, even reversing the effect of the climatic signal, leading for example to streamflow increases when nearby non-glacial rivers experience decreases. Changes in glacier conditions will influence the relations between climate signals and streamflow, with a range of implications for water resources availability, evaluation and management.

Changes in flow regimes could have significant socioeconomic and ecological implications, particularly in the context of power generation. For example, the Columbia River has been extensively exploited for hydroelectric power generation in both Canada and the United States. The Canadian portion of the catchment contains numerous glaciers, but there is uncertainty regarding their current contributions to streamflow and how these may change under future climatic conditions. At a more local scale, run-of-river hydroelectric projects have been proposed for many streams in BC, a large number of which have glaciers in their catchments. In these cases, it is important to recognize that significant changes in flow may occur over the lifetime of the project, particularly when setting targets for flow releases to protect fisheries values between the diversion weir and the powerhouse. Continuing glacier retreat and decreases in summer flow could ultimately reduce the availability of water for power production, at least seasonally and especially during dry weather.

Many standard approaches to water resource analysis, such as low flow and flood frequency analysis, are based on the assumption of stationarity. The occurrence of progressive glacier change during the period of observed streamflow will mean that recorded events will not represent samples from a homogeneous population, introducing an additional source of uncertainty into analysis. Furthermore, future glacier change could amplify nonstationarity associated with climate change. For example, a decrease in glacier cover, in conjunction with earlier snowmelt and reduced summer precipitation, could produce a strong trend to lower summer flows.

Analogous issues apply to river forecasting models, as used for example by water supply utilities, hydroelectric power companies and government flood warning agencies. In catchments undergoing rapid rates of glacier recession, watershed models are likely to become outdated at least every decade or so. The result would in general be an overall decrease in prediction skill. The likelihood of forecast 'busts' may also increase, and could be of particular concern. For instance, in a warm, dry summer following a low-snow winter, higher-than-average flows are likely to occur in glacierized catchments, due to enhanced glacial melt production. The amount of such glacier-generated river discharge enhancement, however, depends on the extent of glacial cover in the basin. Clearly, if a forecast model is predicated on an inaccurately large glacier-covered area, reflecting past (and therefore no longer applicable) glacier conditions, a model overforecast of flows could occur. This forecast error could conceivably lead to incorrect management decisions in the future, such as retaining a water volume in the reservoir insufficient to meet various conjunctive uses, including water supply, hydroelectric power generation and/or downstream aquatic habitat maintenance. The economic and other consequences of even one such event can be severe. For conventional process-oriented models, adaptation would require frequent glacier monitoring and a corresponding process for updating the model land cover characteristics and (probably) recalibration. For traditional statistical models, redevelopment of forecast relationships (e.g. regression equations or neural network architectures and parameters) on a semi-regular basis might be necessary. Development of superior statistical or process-based models, capable of incorporating and making use of more detailed descriptions of current glacier state, could also prove operationally beneficial. The ideal would be a watershed model explicitly incorporating or linked to detailed submodels of (among other things) both glacier dynamics and glacial hydrology.

Hydroecology

Research linking glaciers, water quality, and invertebrate ecology has shown that the low water temperatures and high suspended sediment concentrations of kryal (glacial river) ecosystems is such that biomass and biodiversity tend to be lower, all other things being equal, relative to rhithral (snowmelt dominated) streams (Milner and Petts, 1994; Milner *et al.*, 2001). However, another line of investigation has followed potential linkages between glacial influences on late-summer streamflow volumes and fish abundance and diversity, particularly with respect to salmon spawning requirements. Although there is great variability between species and runs, Pacific salmon tend to migrate to freshwater and spawn in late summer or early autumn. At this time of year, glacial melt typically continues to provide substantial flows and cool water, whereas the freshet in non-glacial (i.e. snowmelt- and/or rain fed) rivers has long since waned and stream temperature has become more sensitive to weather conditions. Aquatic habitat availability at this crucial time of year is therefore greater (again, all other things being equal) in glacier-fed rivers, thus helping to support greater salmon populations in kryal ecosystems in Alaska. Conditions can be particularly favourable if glacial cover is accompanied by lake cover, which mitigates kryal hydroecological liabilities (mainly high sediment concentrations) while maintaining its advantages (augmented late-summer flows and cool water) (Dorava and Scott, 1998; Dorava and Milner, 2000).

In southwest Yukon and northwest BC, a comparison of water resource productivity, flow timing, and fish species presence/absence between nival and glacial catchments suggests that, relative to rhithral systems, glacial rivers support additional aquatic habitat throughout the year (Fleming, 2005). The timing of this effect includes both the usual salmon spawning season, and the winter baseflow season, which is the most taxing time of year in subarctic regions with respect to habitat availability. No systematic differences in fish species richness were detectable between glacial and non-glacial regimes, again implying a diminution or reversal of the situation suggested for invertebrates, and some preliminary evidence for the modifying effects of lake cover was again found. Much additional work on the relationships between glaciers, streamflow, and fish abundance and diversity clearly remains to be done, particularly at more southerly locations in western North America, where many salmon populations are under increasing stress due to factors such as overharvesting and loss of freshwater habitat.

Many aspects of the distribution, life histories and spawning success of salmonids are linked to stream temperature. While the temperature sensitivities to glacier cover appear modest, these sensitivities are similar to changes associated with streamside clearcut logging, which increased MWAT by 1–3 °C for small streams in coastal BC (R. D. Moore, unpublished data). Furthermore, these sensitivities represent an average effect detected by the analysis; sensitivities in some basins would be higher than that suggested by the regression analysis. Finally, even a 2 °C change in MWAT can be ecologically significant. For example, bull trout (*Salvelinus confluentus*), a blue-listed (at risk) species found in the PNW, is generally limited in BC to streams with MWAT less than about 12·5 °C (E. Parkinson, BC Ministry of Environment, pers. comm.). If a stream currently has a MWAT of 11 °C, a warming of 2 °C could produce a competition-driven shift from bull trout to another species such as rainbow trout. Furthermore, even subtle changes in stream temperature regimes can have strong, non-linear and potentially negative ecological effects (Fleming and Quilty, 2007). Further research is needed to quantify the sensitivity of stream temperature to glacier retreat; such assessments should be linked with prediction tools including bioenergetic modelling to help assess the ecological effects of temperature changes.

KEY KNOWLEDGE GAPS AND RECOMMENDATIONS FOR FURTHER STUDY

While considerable attention has been focused on the potential impacts of future climate warming on hydrology and water quality in unglacierized catchments, less attention has been paid to the response of glacier-fed streams. Some progress has been made in modelling the effects of future climate scenarios on streamflow in glacierized catchments, including the effect of transient changes associated with glacier response. However, further model development is required, particularly to improve our ability to predict dynamic glacier response to future climate scenarios. A major challenge to model application is that the presence of glaciers within a catchment greatly increases uncertainties associated with model calibration. Glacier mass balance information is required to help constrain model calibrations and reduce predictive uncertainty. Unfortunately, the sparse network of mass balance sites in western North America presents a severe constraint to our ability to calibrate hydrologic models in glacier-fed catchments, and there is an urgent need to develop approaches for using remotely sensed imagery to assist in calibrating glacier hydrology models.

In comparison to the case for streamflow, there is less capacity for predicting the effects of future climate change and glacier response on stream temperature, water chemistry (including pollutants) and suspended sediment concentrations. While space-for-time substitutions can provide useful qualitative information on the effects of glacier cover on these water-quality parameters, these relations may not be valid for future climatic conditions. Deterministic modelling approaches are necessary to make such extrapolations.

Improving our ability to predict the effects of future climate change and glacier response on hydrology and water quality will require more integrated data collection, including the establishment of monitoring networks on glacier-fed and nearby nonglacier-fed streams to begin collecting the time series data that can be used for testing predictive models. These monitoring networks should encompass streamflow, climate data, glacier state (ideally including some level of mass balance measurement as well as glacier coverage and geometry), and water quality. In addition, process-based studies (e.g. heat budgets for proglacial streams, erosion from recently exposed glacier deposits, biogeochemistry of deglaciated terrain) should be conducted to assist with developing and testing of predictive models.

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