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Suspended sediment dynamics in the proglacial zone of the rapidly retreating Castle Creek Glacier, British Columbia, Canada

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22.1 Introduction

Climate change is affecting our use of water-related resources (IPCC, 2007; Pike et al., 2008; Piao et al., 2010; Jacob et al., 2012; Mernild et al., 2012a). Diminishing snowpacks and receding glaciers (Singh and Kumar, 1997; Demmer and Mooers, 2005; Mernild et al., 2012b, 2013a, 2013b) directly affect water resources, including melt and evaporation in snow and glacier-fed drainage basins (Singh and Bengtsson, 2005); flow regime for fish; soil moisture and aquifer recharge; groundwater reserves; and reservoir levels and water supplies to communities (BCMOE, 2002, 2007).

Recent warming has caused most mountain glaciers on Earth to retreat (Reichert et al., 2002; Zhang et al., 2011; Mernild et al., 2013b). In British Columbia (BC), Canada, glaciers cover about 3% (ca. 29,000 km^2) of the landmass (Moore et al., 2009). The majority of glaciers in BC are recording appreciable area and volume losses (Schiefer et al., 2007; Bolch et al., 2010; Tennant et al., 2012), which are associated with changes in discharge and the timing of peak flows in many rivers in BC and northern Canada (Déry and Wood, 2005; Déry et al., 2009; Moore et al., 2009).

The rapid retreat of mountain glaciers exposes fresh glacial debris that forms an important but poorly understood sediment source to downstream river systems. For example, in the proglacial zone of the Bas Glacier d'Arolla, southern Switzerland, Warburton (1990) reported that proglacial sediment sources contributed 23% to the total basin sediment yield. The overwhelming proportion of the proglacial sediment (95%) was eroded from the valley sandur during a brief period of meltwater flooding between July 15 and 18, 1987. The sediment budget suggested that four basic process subsets could be distinguished: (1) channel processes, (2) valley sandur (channel margin) processes, (3) hillslope processes, and (4) slopewash. Large magnitude, infrequent flood events were the dominant control on the release of sediment from proglacial storage. Building on this, Porter et al. (2010) have suggested that enhanced delivery of water-saturated, ice-marginal sediments to the glacier surface is a response to glacier thinning that has the potential to increase both levels of sediment transfer through the glacier hydrological system and total basin sediment yields. Hodgkins et al. (2003) found that the Finsterwalderbreen proglacial zone, Svalbard, served as both a source and sink for sediment during different periods of the melt season, where the majority of sediment evacuation occurred during periods of high flow and sediment storage varied from year to year. Orwin and Smart (2004) used a network of nine turbidimeters in the Small River Glacier basin, British Columbia, and found that the proglacial area was the source for up to 80% of the total suspended sediment yield transferred from the basin for the 2000 melt season. The unusually warm summer of 2003 in the Ecrins Massif, SE France, caused suspended sediment loads to be three to four times greater than the cooler-than-average 2004 and 2005 ablation seasons in the Torrent du Glacier Noir (Stott and Mount, 2007a, 2007b, 2007c). In the Morteratsch proglacial zone, Switzerland, Stott et al. (2008) reported a clear decline in suspended sediment transport rates between a station 50 m from the glacier snout and another 600 m away across the proglacial zone. In both the Ecrins and Morteratsch studies, however, short but discrete phases

of suspended sediment "flushing" were observed when the net output from the proglacial zone exceeded the net input. These "flushing" phases were normally associated with summer rainstorms and melt-induced high flows.

The preceding review illustrates that proglacial zones can act as both a sink and a source of sediment, which varies both spatially and temporally in response to changes in glacier dynamics (e.g., melt) and hydroclimatic conditions (e.g., rain events). Given these varied findings, a better understanding of the processes of sediment exchange (sources, fluxes, and storage) in proglacial zones could improve predictive modeling of river sediment dynamics and how these dynamics affect downstream aquatic ecology and water resources (Milner et al., 2009; Moore et al., 2009; Owen et al., 2009).

This chapter draws together and compares data on sediment fluxes gathered in two melt seasons, 2008 and 2011, in the Castle Creek Glacier proglacial zone, BC, to examine the relative importance of snow/ice melt events and summer rainfall events on the suspended sediment dynamics at three locations within the proglacial zone. Specific research objectives were:

1) How do suspended sediment concentrations and fluxes compare between the two field seasons given the difference in hydroclimatic conditions?
2) Is the proglacial zone a net source or sink of suspended sediment?

22.2 Study area and methods

Castle Creek Glacier (53°2' N., 120°24' W., unofficial name) has an area of 9.5 km^2, a length of 5.85 km, and an elevation range of 1,830 to 2,827 m above sea level (a.s.l.) and is located in the Cariboo Mountains of eastern BC (Fig. 21A, Fig. 22; Table 22.1). The

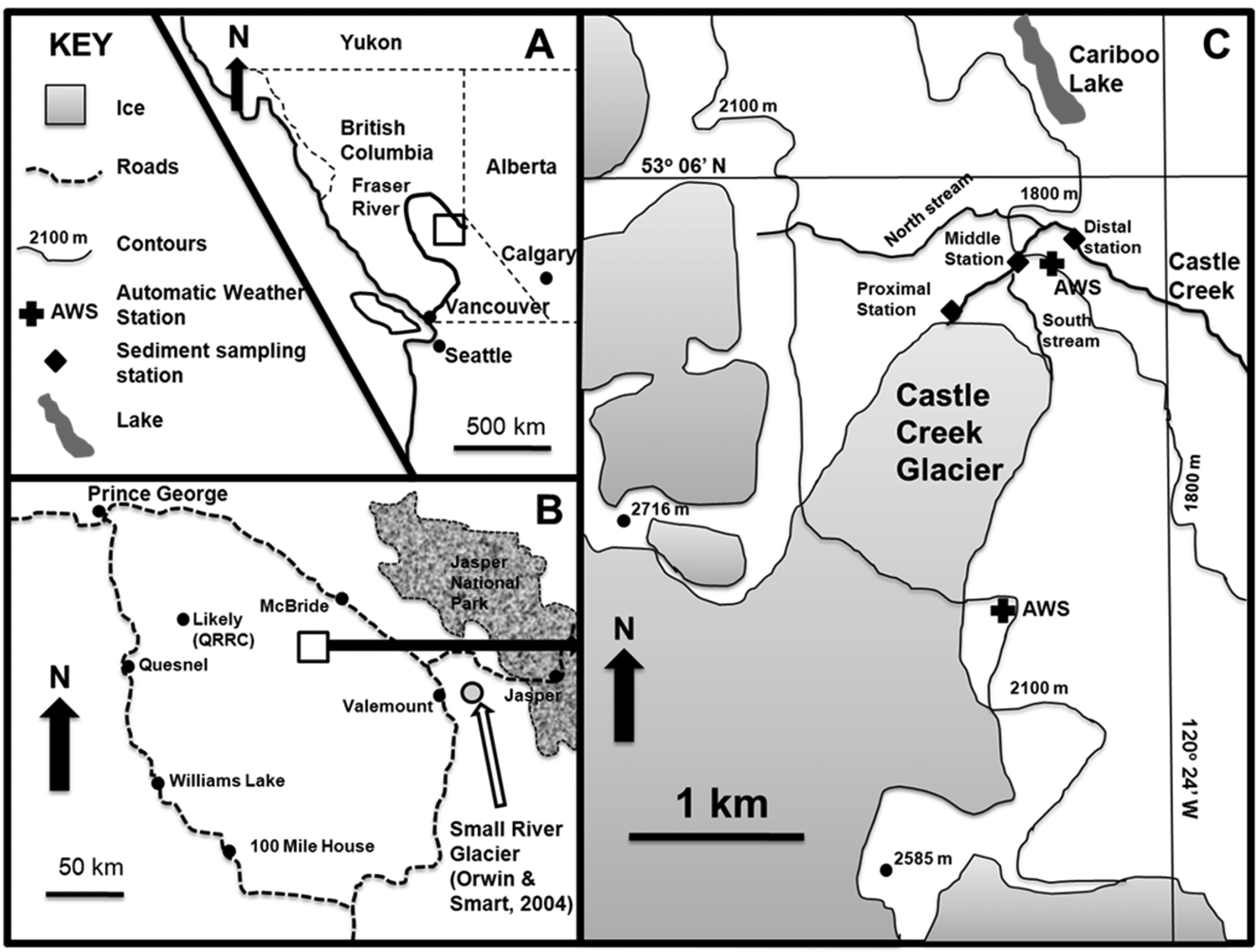

Figure 22.1A–C Study location in British Columbia, Canada.

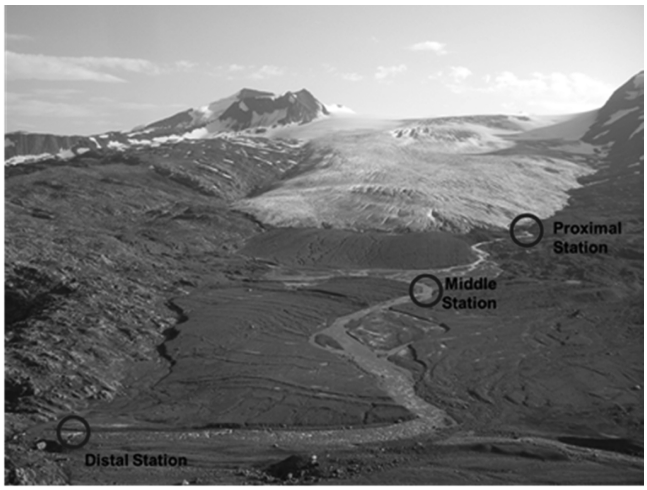

Figure 22.2 View of Castle Creek Glacier fore field from halfway up peak 2,779 m taken on July 16, 2008. Sampling site locations (and altitude): Distal station: N 53° 03' 52.3", W 120° 25' 53.3" (1,793 m); Middle Station and Proximal station: N 53° 03' 43.3", W 120° 26' 07.9" (1,797 m); View is looking approximately southwest.

glacier is located about 180 km SE of Prince George, 35 km south-southwest (true course 210°) of McBride, and 10 km NE of Roberts Peak (2,700 m a.s.l.). Beedle et al. (2009) used a series of annual push moraines (Fig. 22.2) and aerial photographs to determine that the glacier had retreated c. 886 m between 1946 and 2007; an average of 14.3 m a^{-1}. The melt water draining from Castle Creek Glacier forms the Castle Creek stream, which flows northeast for c. 34 km into the Upper Fraser River, which drains into the Pacific Ocean at Vancouver, BC. The Fraser River drains ca. 220,000 km^2 of BC and is a nationally important river for Pacific salmonids and other fish (e.g., sturgeon) and as a freshwater resource for the 2.8 million people that live in its watershed. Consequently, there is much concern associated with the potential impacts of climate change on river flows and sediment fluxes in the Fraser Basin (FBC, 2007; Moore et al., 2009).

In a preliminary publication (Stott et al., 2009), we reported data and a preliminary analysis for three monitoring stations shown in Figures 22.1C and 22.2A, which were named Proximal (50 m from glacier snout in 2008), Middle (660 m from glacier), and Distal (1,230 m from glacier) when monitoring was carried out over 34 days in July–August 2008. Based on lessons learned during our preliminary field campaign in 2008 (Stott et al., 2009), we conducted a second, more intensive and longer field campaign

Table 22.1 *Catchment characteristics for Castle Creek Glacier, British Columbia. (53° 2' N., 120° 24' W)*

Glacier area	9.5 km^2
Glacier length	5.85 km
Elevation range	2827 to 1830 m
Elevation of proglacial zone	1830 to 1790 m
Proglacial zone gradient	Average 0.04 m/m
	Proximal – Middle 0.06 m/m
	Middle – Distal 0.02 m/m

(60 days) in July–September 2011, during which we measured suspended sediment fluxes at six stations within the proglacial zone (Leggat et al., 2015), three of which were at the same locations that we sampled in 2008 (Fig. 22.1C).

In 2008 stream discharge (Q) was gauged at the distal station (Fig. 22.2), which was 1,230 m downstream from the glacier snout where the stream was 9.5 m wide prior to the river entering a narrow gorge 2–3 m wide. A stage board and Druck pressure transducer stage recorder (± 2 mm resolution) were installed at this location upstream of the gorge. The channel depth and velocity at 0.6 m water depth were surveyed at 0.5 m intervals on 12 occasions over Q that ranged from 1.23 to 2.16 m^3 s^{-1}. The velocity-area method (Herschey, 1978) was used to estimate Q, and a stage-discharge rating curve was established ($R^2 = 0.87$, $n = 12$, $p < 0.001$). Due to safety considerations, we were unable to survey periods of Q above 2.16 m^3 s^{-1}, and thus we extrapolated the curve for higher flows. Due to data logger malfunction, hourly stage values were manually recorded from July 9–18, 2008, after which the data logger problem was resolved and stage was logged electronically until August 12, 2008. Although the focus of the 2008 and 2011 studies was on the proglacial zone upstream of the gorge, the distal suspended sediment monitoring site was located downstream of the gorge to ensure complete mixing of suspended sediment in the flow. In 2008 the absence of measurements of Q at the proximal and middle stations required us to estimate values of Q for the proximal station by subtracting the mean gauged Q of South Stream (the main tributary between these two sites; see Fig. 22.1C, 22.6A), estimated at 23% of the distal Q (Stott et al., 2009), from the distal Q. Discharge at the middle station was estimated by subtracting the mean gauged discharge of the North

stream (the main tributary between the middle and distal sites), estimated as 15% of the Q at the distal station (see Stott et al., 2009) from Q at the distal station. In 2011, streamflow (Q) was gauged at the same three locations as in 2008. In 2011, sites were equipped with stage boards, Hobo U20 pressure transducers (± 4.5 mm), which were fixed vertically in stilling wells, thus flow was gauged (details are given in Leggat et al., in review) and stage-discharge rating curves were established.

Teledyne ISCO automatic pump samplers located at each monitoring station (in 2008 and 2011) obtained 0.8 L water samples. The 3–4 m long intake pipes were fitted with 3 mm gauze at the sampling end and fixed to large boulders in the creek so that they remained at least 0.1 m from the bed, but stayed within the flow at all times during the study. In 2011, the sample intake points were suspended from a float at a set depth from the water surface to avoid the effect of saltation near the streambed.

We assumed that because of the highly turbulent nature of the flow, suspended sediment is laterally well mixed (Gurnell et al., 1992; Navratil et al., 2011). All water samples were filtered through Whatman GF/D 8 μm filters in the field, and filters were returned to the laboratory at the University of Northern British Columbia (UNBC) for gravimetric analysis of suspended sediment concentration (SSC). Oven drying and repeat weighing of filters suggested that standard errors were ± 0.15 mg. We therefore estimate that suspended sediment processing is likely to be associated with errors of ± 10 mg, and the measurement of volume ± 5 mL, giving a combined SSC error of about 3% (Collins, 1979). These SSC samples were paired with the synchronous turbidity values obtained from 0–10 000 mg L^{-1} range. Partech turbidity sensors for the Middle and Distal sites in 2008, and thus turbidity data were calibrated to represent SSC. Leggat et al. (2015) describe the deployment and operation of turbidity sensors in 2011, following a similar procedure.

We used 8 μm filters to facilitate filtering a large number of samples by hand in a remote field setting and to allow comparison to the nearby study of Orwin and Smart (2004). To determine the proportion of fine silt and clay that may have passed through the 8 μm filters (as also used by Orwin and Smart, 2004), we passed an additional 22 water samples (SSC varied from <100 to >1600 mg L^{-1}) first filtered with 8 μm filters through 0.45 μm filters in the UNBC laboratory. The mean amount of sediment within the range 8 to 0.45 μm was 6.9% (SD = 4.0%) and indicates that the use of 8 μm filter papers underestimated the SSC by about 7%. The magnitude of this bias is similar to that observed for a proglacial river in Europe (Stott and Mount, 2007a).

Meteorological data were collected from two automatic weather stations (AWS), one located on a bedrock ridge on the south side of the Castle Creek glacier at 2,105 m a.s.l., and the other on the low gradient till apron near the middle site, c. 1,800 m a.s.l. (Fig. 22.1C). These stations are part of the Cariboo Alpine Mesonet operated by UNBC (Déry et al., 2010). The AWSs measured wind speed and direction, snow height, liquid precipitation (rainfall equivalent), air temperature, solar radiation, humidity, and atmospheric pressure. These meteorological parameters relate to snow and glacial ice accumulation and melt, and surface runoff, and thus assisted us in determining the temporal and spatial pattern of streamflow and sediment flux processes.

22.3 Results and discussion

22.3.1 Meteorological conditions

Daily rainfall totals and daily mean air temperature for the dates in the 2008 and 2011 field seasons, which overlapped (July 14–August 11) are shown in Figure 22.3A; we focus on this period of overlap to compare the suspended sediment dynamics in the proglacial zone during the two field seasons. Clearly the 2011 study period was considerably wetter than the 2008 study period, and Table 22.2 shows that the rainfall total for the 2011 period was 149.1 mm, whereas it was only 7.4 mm for the 2008 period. To put these figures into some kind of context, Table 22.3 presents 10 years of climate data for Prince George in Northern BC (see Fig. 22.1) for the field monitoring period (i.e., July–August). These data confirm that, indeed, 2011 was a wet year, the wettest over the 10-year period (2004–13) with more than double the 10-year average rainfall. However, Table 22.3 also shows that Prince George received 49 mm of rain

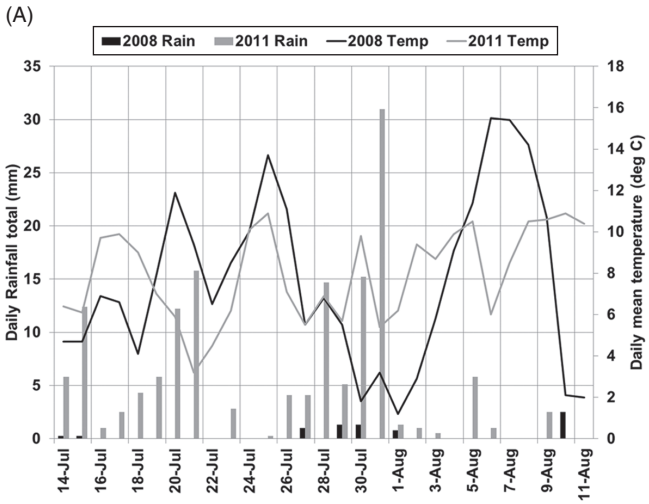

Figure 22.3A Daily rainfall total and daily mean air temperature at upper AWS in the Castle Creek glacier forefield, July 14–August 11 for 2008 and 2011.

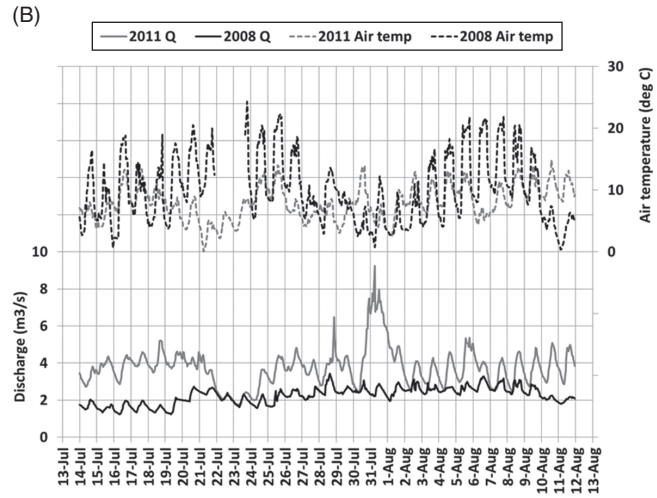

Figure 22.3B Time series plot of distal station discharge and AWS air temperature for 2008 and 2011 melt seasons (15-min data).

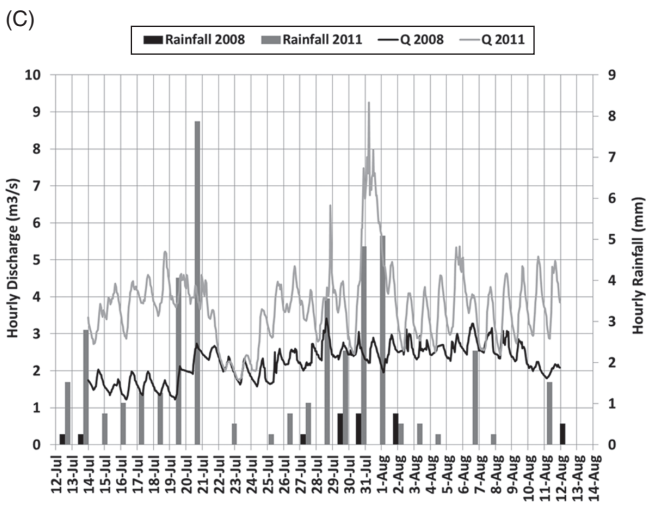

Figure 22.3C Discharge at distal station and AWS rainfall, Castle Creek glacier forefield, 2008 and 2011.

in the period July 14–August 11, 2008, whereas Table 22.2 shows that only 7.4 mm was recorded at the field site AWS. So, as ever, caution should be exercised when comparing data in mountain environments with weather stations in lowland areas some distance away. The Castle Creek data indicate that 2011 was unusually wet.

The 2008 field season had three warm phases (Fig. 22.3A), where peak temperatures on July 20, July 25, and August 6 were considerably above average and temperatures remained higher than in 2011 for several days (e.g., July 19–23 and August 5–8), although the mean temperature for the whole field period (Table 22.2) was slightly lower (7.6°C) in 2008 than in 2011 (8.0°C). However, photographs taken on July 16 in both 2008 and 2011 (Fig. 22.7C and D) show more snow lying on and adjacent to the glacier in 2011, which could indicate cooler conditions before the field campaign started, or that more snow fell during the previous winter. Again, these higher temperature phases will be examined in detail later and compared with discharge and suspended sediment flux in the streams.

22.3.2 Streamflow

The time series plot of Distal station discharge (Q) and AWS air temperature (T_{air}) for 2008 and 2011 melt seasons (Fig. 22.3B) shows a marked diurnal pattern in T_{air}, though rainfall shown alongside Q in Fig. 22.3C disrupts this pattern, particularly in 2011. Table 22.2 shows that distal Q_{mean} was 2.2 m^3s^{-1} in 2008 and 3.8 m^3s^{-1} in 2011, which was a consequence of the much higher rainfall in the 2011 season. The hourly averaged Q_{max} in 2011 was 9.3 m^3s^{-1}, almost three times higher than the 2008 Q_{max}, which was 3.4 m^3s^{-1} (Table 22.2).

Table 22.2 *A comparison of 2008 and 2011 meteorological factors, stream discharge, and suspended sediment concentration and load for Castle Creek glacier forefield between July 14 and August 11 in both melt seasons*

			Proximal	Proximal	Middle	Middle	Distal	Distal
JULY 14–AUG 11	2008	2011	2008	2011	2008	2011	2008	2011
RAIN								
Rainfall Total (mm)	7.4	149.1						
Mean Hourly Total (mm)	0.01	0.2						
Max Hourly Total (mm)	0.8	7.9						
AIR TEMPERATURE								
Mean (deg C)	7.6	8.0						
Max (deg C)	19.1	14.8						
Min (deg C)	–0.6	0.0						
DISCHARGE								
Mean (m^3s^{-1})			1.4	2.7	1.9	3.2	2.2	3.8
Max (m^3s^{-1})			2.1	5.9	2.9	7.6	3.4	9.3
Min (m^3s^{-1})			0.8	1.4	1.0	1.6	1.2	1.8
SSC								
Mean (mg L^{-1})			241	99	313	114	430	183
Max (mg L^{-1})			374	252	498	329	609	805
Min (mg L^{-1})			128	56	159	50	263	16
SSL								
Mean (kg h^{-1})			1265	1006	2245	1407	3592	2723
Max (kg h^{-1})			2871	5385	5206	9355	7498	28496
Min (kg h^{-1})			351	290	598	340	1160	405
TOTAL SSL (t)			880	700	1562	978	2500	1896

Table 22.3 *Climate at Prince George (Latitude 53° 88' N, Longitude 122° 68' W, Altitude: 691m a.s.l.) during the study period, Jul 14–Aug 11, over 10 years (2004–13)*

July 14–August 11	Mean daily temperature (°C)	Max daily temperature (°C)	Total precipitation (mm)	Max daily precipitation (mm)
2004	16.9	21.2	38.1	13.7
2005	14.9	18.4	38.5	13.7
2006	15.4	25.1	56.3	14.5
2007	15.8	23.9	38.8	9.6
2008	**15.8**	**21.2**	**49.0**	**10.9**
2009	18.7	22.2	24.1	11.9
2010	17.1	23.2	10.9	12.9
2011	**14.1**	**24.2**	**86.2**	**13.9**
2012	17.1	25.2	26.2	14.9
2013	18.1	26.2	31.0	15.9
10-year Mean	16.4	23.1	39.9	13.2
10-year Max	18.7	26.2	86.2	15.9
10-year Min	14.1	18.4	10.9	9.6

Data accessed online from http://www.tutiempo.net/en/Climate/.

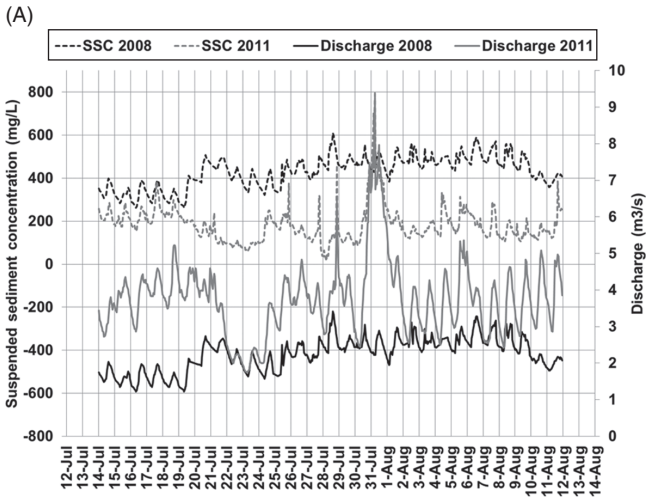

Figure 22.4A Suspended sediment concentration and discharge at distal station, Castle Creek glacier forefield, 2008 and 2011.

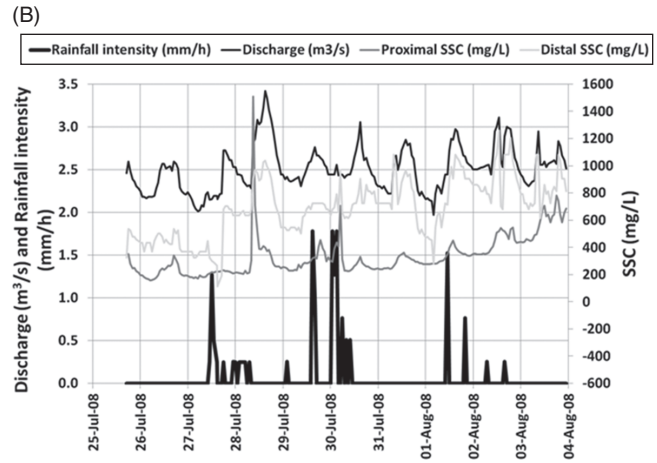

Figure 22.4B Rainfall intensity (mm/hr), suspended sediment concentration (SSC), and discharge (Q) at proximal and distal station 2008.

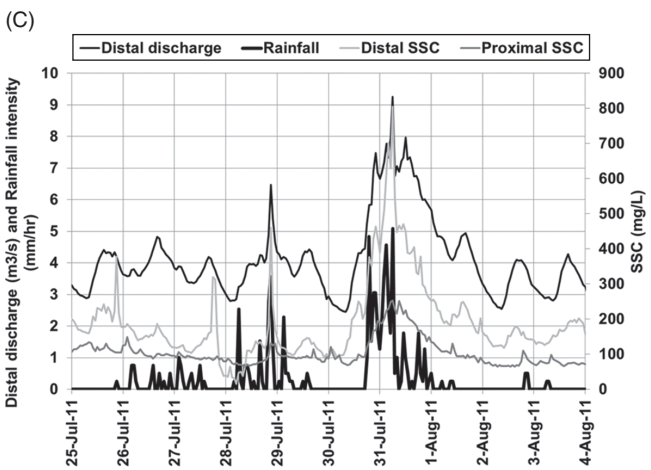

Figure 22.4C Rainfall intensity (mm/hr), suspended sediment concentration (SSC) and discharge (Q) at proximal and distal station 2011.

22.3.3 Suspended sediment concentration (SSC)

With the exception of the flood event that peaked on July 31, 2011, Fig. 22.4A shows that distal SSC in 2008 was consistently higher than in 2011, despite the much lower Q (as discussed in the previous section), which is plotted alongside SSC in Figure 22.4A for both seasons. Distal SSC_{mean} was 430 and 183 mg L^{-1} for the 2008 and 2011 seasons, respectively (Table 22.2) with Distal SSC_{max} being 609 and 805 mg L^{-1} in 2008 and 2011. One possible reason for this could be that the water sampler intake pipes in 2008 were located 0.1 m from the riverbed, whereas in 2011 they were suspended from a float 0.1 m below the water surface. This could potentially explain the differences we observed between the two seasons. For example, in a separate study in Greenland in 2009 (Stott et al., 2014) samples were taken using this same method, which we used at Castle Creek in 2011 (sample intake suspended on a float 0.1 m from the water surface), and the mean SSC value (n = 57) estimated by this method was 25.4 mg L^{-1}, whereas the mean SSC for 57 samples taken at the same time with a USDH-48 sampler operated next to the suspended sampler intake was 40.1 mg L^{-1} and the Student t-test showed that these means were not significantly different. However, SSCs were significantly lower in the Greenland study than at Castle Creek (see Table 22.2) so, even using these data, it is impossible for us to discount the possibility that the different positions of the water sampling intake tubes at Castle Creek in 2008 and 2011 relative to the riverbed may be able to explain the differences in our SSC data for the two field seasons. Having said this, we will continue to compare the SSC data for the 2008 and 2011 field campaigns making the assumption that the sampling locations does not entirely account for the observed differences.

Rainfall intensity (mm hr^{-1}), SSC, and Q at the proximal and distal station are plotted for the 2008 (Fig. 22.4B) and 2011 (Fig. 22.4C) monitoring periods to give a more detailed insight into the suspended sediment dynamics in the glacier forefield in both

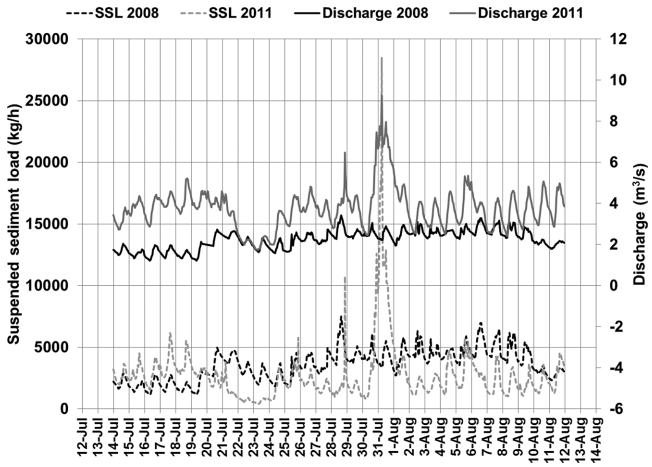

Figure 22.5 Suspended sediment load and discharge at distal station, Castle Creek glacier, 2008 and 2011.

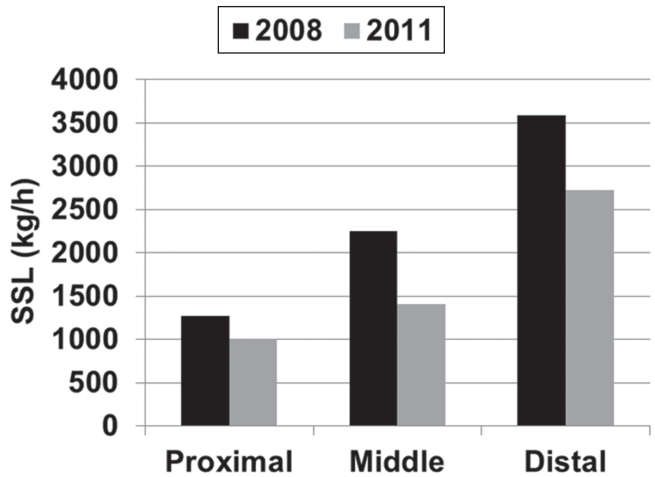

Figure 22.6 Suspended sediment loads at the proximal, middle, and distal sampling stations for 2008 and 2011 compared.

seasons. In 2008 the highest Q peaks are caused both by high air temperatures as well as rain events, whereas in 2011 the rain events are more closely linked with the highest Q events. Because proximal SSC is plotted as well as distal SSC, it can be seen that distal SSC is almost always considerably higher than proximal SSC, and both distal and proximal SSC peaks more or less coincide with Q peaks. The difference between our proximal and distal observations is a function of sediment dynamics between the two sites (e.g., balance between sediment deposition and remobilization) and new sources (e.g., erosion of channel banks), as well as inputs from tributaries (e.g., North and South stream, Fig. 22.1).

22.3.4 Suspended sediment loads (SSLs)

When Q and SSC are combined to calculate suspended sediment loads (SSLs; Fig. 22.5), the significance of the rainfall-discharge event that peaked on July 31, 2011 on sediment transport is clear. The 2011 Q rises from a background of between 3 and 6 m^3s^{-1} to over 9 m^3s^{-1}, and SSL rises from a background of between 1,000 and 5,000 kg h^{-1} to peak at over 28,000 kg h^{-1}. This event, which, from the first rise in Q, lasted from 06:00 on July 30, 2011 until 06:00 on August 2, 2011 (i.e., in terms of time this was 10.3% of the total 29-day period) transported 23.7% of the total SSL for the 29-day period analyzed here. In comparison, Liermann et al. (2012) reported that 61.9% of the 2010 annual suspended sediment yield was associated with summer glacier melt, and 19.8% of the 2010 annual suspended sediment yield was due to single rainfall events in the Sætrevatnet subcatchment in western Norway.

At Castle Creek the SSL_{totals} for 2008 and 2011 are shown in Figure 22.6. Considering the large differences in rainfall and Q between the two seasons as discussed earlier, the difference between the SSLs at all three sites is relatively small. In both seasons, the SSL increases from the proximal to the middle station, and again from the middle to distal station, suggesting that in both seasons the difference between our proximal and distal observations is a function of sediment dynamics between the two sites (e.g., balance between sediment deposition and remobilization) and new sources (e.g., erosion of channel banks) as well as inputs from tributaries (e.g., North and South streams, Fig. 22.1). So, it is tempting to conclude from this simple comparison that more rainfall and higher Q (i.e., the wetter climate of 2011) has not significantly increased SSLs delivered from the Castle Creek glacier forefield to the river downstream. In fact, distal SSL_{total} in 2011 was 75.8% of the 2008 distal SSL_{total} over 29 days, even though the 2008 Q_{total} was only 59.6% of the 2011 Q_{total}. Table 22.2 shows that the total proximal SSL for 2008 was 880 t compared with 700 t in 2011. This suggests that the warmer, drier 2008 monitoring period enhanced subglacial erosion and sediment transport processes to our proximal station as compared with 2011. Periods of higher temperature in 2008 presumably mobilized the glacier bed and

(A)

Figure 22.7A View of till sheet between proximal and middle station: an important sediment source, viewed looking upstream, July 2008, taken by T. Stott.

(B)

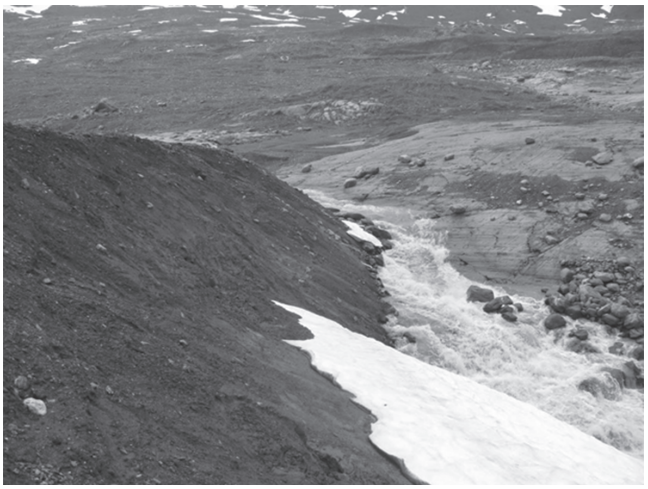

Figure 22.7B View of till sheet between proximal and middle station viewed looking upstream, July 2011, taken by T. Stott.

increased suspended sediment load at our proximal site. However, the processes within the proglacial zone (i.e., between our proximal and middle site, and between our middle and distal site), appear not to have changed dramatically; indeed, the relative increase in SSL between the proximal and distal sites for both years is similar at ca. 2.8 and 2.7 for 2008 and 2011, respectively. Figure 22.7A and B show photographs of the till sheet between the proximal and middle station, which is an important sediment source, but which appears to have remained stable between July 2008 and July 2011.

There has been much speculation about how a future warmer or wetter climate might impact on sediment transport in rivers, and indeed in proglacial zones. Arnell and Goslin (2013) concluded that "most climate models project increases in runoff in Canada and high-latitude eastern Europe and Siberia" (p. 1), so data like these presented here for Castle Creek glacier, which compares proglacial sediment transport in wetter and drier seasons, provides a useful insight into suspended sediment transport responses to different rainfall regimes.

It has been widely assumed that accelerated glacier melt due to climate change can lead to an increase in suspended sediment discharge from proglacial zones (e.g., Stott and Mount, 2007a). However, Geilhausen et al. (2013), working at the retreating Obersulzbachkees Glacier, Hohe Tauern, Austria, demonstrated that the connectivity between glacial sediment production and downstream sediment fluxes during deglaciation is significantly reduced by the development of proglacial lakes. They showed using systematic up- and downstream sampling that the proglacial lake in their study site reduced SSCs by 88–95%, though they also noted that in some situations, such as during rainfall-induced hillslope sediment supply, the lake changed from a sink to a temporary source. Stott et al. (2014) drew similar conclusions in SW Greenland. The enlargement of the proglacial lake at Castle Creek glacier snout between 2008 and 2011 (see Fig. 22.7C and 22.7D) is likely to be storing some sediment transported from the Castle Creek Glacier, and this should be born in mind when comparing the 2008 and 2011 data sets. Hasholt et al. (2000), among others, have used sedimentation rates in proglacial lakes to infer catchment denudation rates, and this may be an avenue for future research at Castle Creek given the development of at least one proglacial lake (Fig. 22.7C and Fig. 22.7D). Anderson et al. (2000) examined chemical forefield rates and strontium isotope ratios in streams in the foreland of the retreating Bench Glacier in south-central Alaska and found that (1) both sediment age and vegetation cover increase with distance from the glacier, and (2) cation denudation rates decline with increasing distance from the glacier, whereas silica denudation rates increase. Further work

(C)

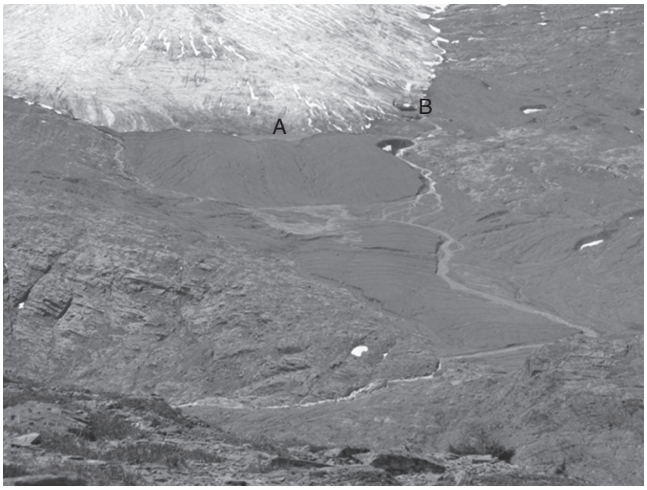

Figure 22.7C View of Castle Creek glacier proglacial zone with recessional moraines in foreground. A marks the position of an ice marginal lake; B marks the Proximal sampling site. Photograph date: July 16, 2008, taken by T. Stott.

(D)

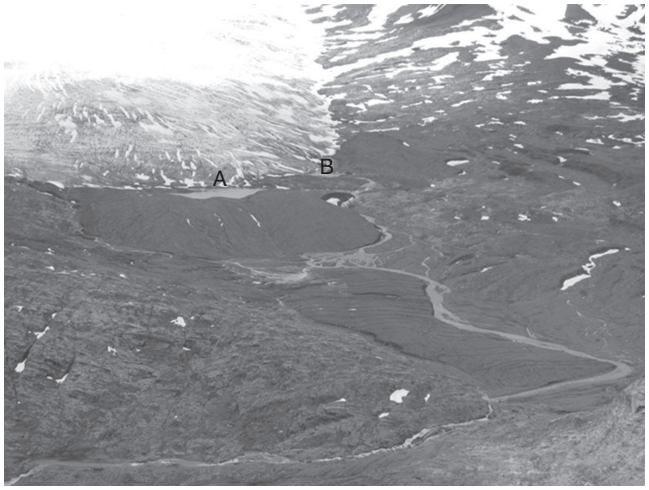

Figure 22.7D View of Castle Creek glacier proglacial zone with recessional moraines in foreground. Note the slightly larger lake at the center of the glacier snout (compared with Figure 22.7C in 2008) and the enlargement of the ice marginal lake at A and the appearance of a new lake at B. We estimate that the glacier snout had receded by an average of 50 m between 2008 and 2011. Photograph date: July 16, 2011, taken by T. Stott.

to investigate the chemical weathering rates and solute transport in the proglacial streams of Castle Creek glacier would help to refine our sediment budget considerably.

22.3.5 Downstream implications

Increases in suspended sediment fluxes from mountain regions can result in high sediment transport rates and sedimentation in downstream reaches of rivers, such as the Fraser (into which Castle Creek flows), which may affect aquatic ecology. Enhanced fluxes of fine-grained sediment (e.g., from anthropogenic land use change) can clog riverbed gravels, which in certain reaches contain salmon spawn, depriving the eggs of vital oxygen and thus jeopardizing successful salmon reproduction (Rex and Petticrew, 2008). River sedimentation can also impact channel dynamics in lowland river systems by causing decreases in channel capacity, which can increase flood potential and lateral erosion and may require expensive river dredging programs to avert such problems (Owens et al., 2005).

Although glacier recession is likely to have immediate short- to medium-term (i.e., 10^1 to 10^2 years) impacts on proglacial streams, such as increases in water flows and sediment fluxes, it is likely that such fluxes will eventually stabilize and then decrease, as has been documented for several basins in BC (cf. Casassa et al., 2009; Moore et al., 2009). However, in larger river basins that contain a considerable number of glaciers, there are also likely to be impacts in middle and lowland reaches, which may be of longer duration (i.e., 10^2 to 10^3 years). Church and Slaymaker (1989) described how many of the larger rivers in BC are in disequilibrium, still responding to paraglacial effects, with downstream increases in specific sediment yield in response to the reworking of stored sediment deposits. It may be that the rapid retreat of mountain glaciers creates an additional supply of sediment to the mountain rivers of western Canada that moves through larger drainage basins, such as the Fraser, over the next few decades to centuries.

22.4 Conclusions

This chapter compares suspended sediment fluxes in the proglacial zone of a rapidly retreating glacier in British Columbia for two field seasons, 2008 and 2011. Although the field campaigns in 2008 and 2011 were of different lengths, only data collected between the overlapping dates (July 14–August 11)

are used in this analysis. Broadly the same sampling strategies were adopted in both seasons, with proximal, middle, and distal sampling stations reused in 2011. In 2008 the water sampler intake pipe from the ISCO samplers used was fixed 0.1 m from the bed, whereas in 2011 it was suspended from a float to be 0.1 m below the water surface. This difference in sampling technique could go some way to explaining the different findings between the two years.

Considering the large differences in rainfall and Q between the two seasons, the difference between the SSLs at all three stations is relatively small. SSL increases in both seasons from the proximal to the middle station, and again from the middle to distal station, suggesting that in both seasons the difference between our proximal and distal observations is a function of sediment dynamics between the sites and new sources such as erosion of channel banks, as well as inputs from tributaries. So, it is tempting to conclude from this simple comparison that more rainfall and higher Q (i.e., the wetter climate of 2011) has not significantly increased SSLs delivered from the Castle Creek glacier forefield to the river downstream, and that warm dry conditions are equally capable of generating and delivering suspended sediment to the distal station more than 1 km from the glacier. Important, despite operational differences between the two field season, is that suspended sediment fluxes increase along the proglacial zone, suggesting that it is acting as a source of sediment in the proglacial zone of a retreating glacier.

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