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Interdecadal patterns of total sediment yield from a montane catchment, southern Coast Mountains, British Columbia, Canada

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ABSTRACT

We reconstruct sediment yield for a mountain watershed of western Canada since the mid-twentieth century from studies of annually laminated lake sediments, delta progradation, and solute transfer. Total yield averaged 320 ± 40 Mg km^{-2} a^{-1} and comprised ~35% suspended load, 50% bedload, and 15% dissolved load. Ratios between the individual yield components varied approximately threefold at interannual timescales because of significant variability in the suspended and bedload fractions. Asynchronous flux in suspended and bedload fractions through time arise from differences in sediment availability and transitory sediment storage in the channel. Periods of elevated yield coincide with rapid glacier recession, an extreme rainstorm, and a landslide. Our results indicate that in montane environments, extrapolation from even decade-long monitoring programs may lead to biased projections of long-term yield and delivery mode proportions if variations in sediment supply and catchment response to hydroclimatic and geomorphic controls are not considered.

1. Introduction

Sediment yield, defined as the total outflow of sediment from a catchment per unit time, integrates the intensity and pattern of catchment denudation and sediment delivery over time. Three components of sediment flux in rivers—the suspended load, bedload, and dissolved load—together represent the total fluvial delivery from a drainage basin. Mountain streams supply a disproportionate sediment load to continental margins, yet they are underrepresented in global monitoring programs (Milliman and Syvitski, 1992). Reconstructions of total yield are of interest for montane catchments because both the amount and the mode of sediment transport may be sensitive to land use and climate change (Slaymaker and Owens, 2004).

Most sediment yield data are derived from either suspended or dissolved river loads and rarely are all three components measured simultaneously (Walling and Fang, 2003; Meybeck and Vörösmarty, 2005). Short-term bias also impedes most monitoring programs, which limits their potential to infer long-term change in rates of sediment transfer (Caine, 2004). Accurate estimation of sediment yield from montane catchments is further complicated because transport formulae are notoriously unreliable and operational challenges impede conventional monitoring (Gomez and Church, 1989; Meybeck et al., 2003). Because of these limitations, ratios between river load components are commonly assumed to be constant over time, often with little empirical or theoretical support. In some cases, long-term yield records can be recovered from depositional systems, such as lakes and deltas (Duck and McManus, 1994; Loso et al., 2004; Pratt-Sitaula et al., 2007), which can address some of the limitations that face conventional monitoring programs.

In this paper, we examine the interannual variability of sediment yield for Fitzsimmons Creek, a mountain stream of western Canada, since the mid-twentieth century. We derive suspended, bedload, and dissolved load fractions of yield (respectively) from studies of lake sedimentation, delta progradation, and solute monitoring. The integration of these data presents a unique opportunity to assess the long-term dynamics of total fluvial load for the catchment. Our integrated yield record is related to hydroclimatic trends and geomorphic events to examine how these factors affect the quantity and mode of sediment delivery through time.

2. Study area and methods

2.1. General setting

Fitzsimmons Creek, the primary inflow to oligotrophic Green Lake, drains 95 km^2 of the south Coast Mountains near the resort town of Whistler, British Columbia, Canada (Fig. 1). Bedrock geology is typical of the Coast Plutonic Complex, consisting of granodiorite to quartz

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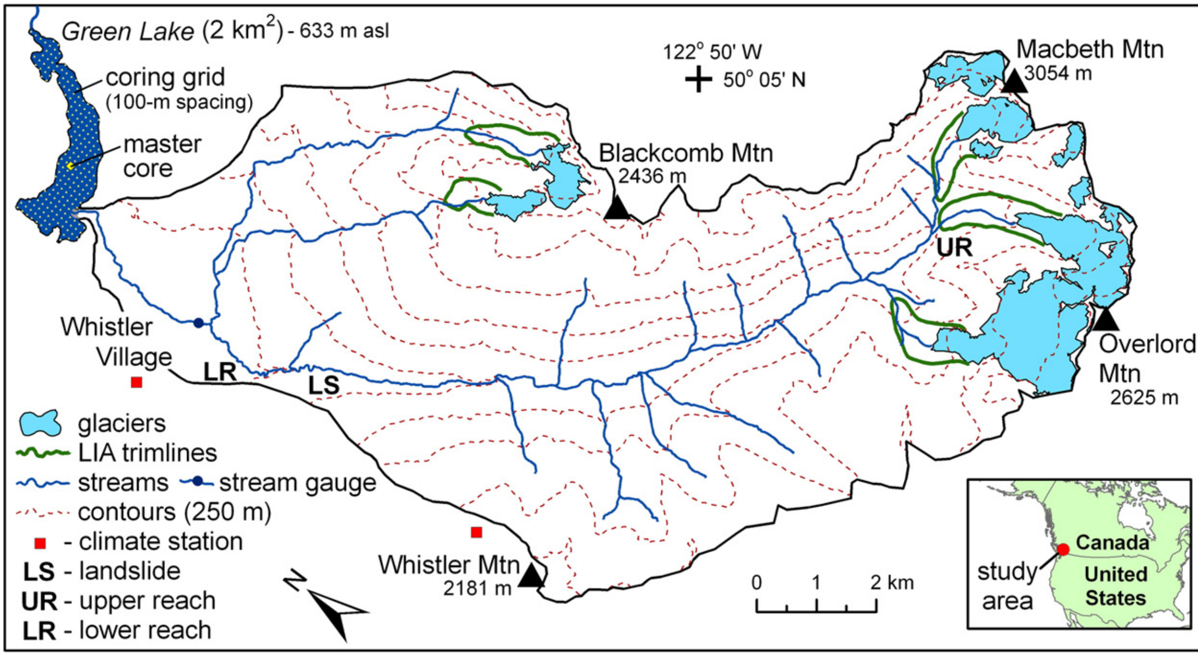

Fig. 1. Catchment area map for Fitzsimmons Creek, British Columbia, Canada. Percussion cores and recent gravity cores were collected from Green Lake at the site marked "mater core", where contemporary sedimentation has been representative of overall lake deposition (Schiefer, 2006a,b,c). LS marks the position of a deep-seated landslide within the Quaternary fill of the lower valley that was activated in August 1991. UR and LR are upper and lower reaches, respectively, of the creek where channel changes have been observed from historical air photos.

diorite intrusions with pendants of metasedimentary and metavolcanic rocks (Monger and Journeay, 1994). Major sediment sources to the creek include alpine glaciers, Little Ice Age glacier forefields, till and colluvium along valley margins, and incised Quaternary fill in some lower valley reaches. Glacier cover for the catchment was ~7% near the end of the twentieth century and ~15% during the early eighteenth century (Koch et al., 2007). Logging took place in the lower valley during the 1950s and 1960s, but most activity occurred on terrace surfaces decoupled from the creek.

Meteorological records, obtained from 658 and 1835 m above sea level (asl) adjacent to the study catchment (Environment Canada stations 1048898 and 1108906, Fig. 1), show that the local temperate–maritime climate is subject to strong altitudinal gradients in temperature and precipitation. At 658 m asl, mean annual precipitation is 1230 mm (~30% snowfall) and mean monthly temperature ranges from 16.1 °C in August to −3.2 °C in December. At 1835 m asl, mean annual precipitation is 1560 mm (~70% snowfall) and mean monthly temperature ranges from 10.1 °C in August to −5.3 °C in January. Streamflow records in the region are characterized by low flows during the winter, high flows in the late spring and early summer during the freshet, and infrequent rainstorm-generated floods during the late summer and autumn (Schiefer et al., 2006). By volume, annual runoff is dominated by snowmelt-generated flows; however, highest magnitude discharges are associated with episodic, rainstorm-generated floods. Based on a streamflow record from 1994 to present (Water Survey of Canada gauge MG026), mean annual discharge of Fitzsimmons Creek near Whistler Village is 4 $m^3\ s^{-1}$, and the one-day mean annual flood is 17 $m^3\ s^{-1}$.

2.2. Suspended load

Most of the suspended load from Fitzsimmons Creek accumulates in Green Lake as annually resolvable couplets (varves) of silt and clay (Menounos et al., 2005). Evidence that the couplets represent varves include (i) independently derived ages obtained using ^{137}Cs activity of the sediments; (ii) the presence of two dated anthropogenic markers observed in some nearshore sediment cores; and (iii) new couplets being predictably observed in cores taken in subsequent years (Schiefer, 2006a). The lack of intervening water bodies or active floodplains between the lake and sediment source areas suggests that the intermediate storage potential of silt and clay is low.

Methods used to derive annual sedimentation rates for Green Lake from 1930 to 2000 are described in detail elsewhere (Menounos et al., 2006; Schiefer et al., 2006). Gravity coring was conducted on a 100-m sampling grid to examine sedimentation patterns at 202 sites in the 2.0 km^2 lake. Cores were split lengthwise with one-half repeatedly photographed while drying to reveal faint sedimentary structures only visible in a partially dried state, and the other half subsampled for bulk physical properties every 2.5 cm downcore using standard methods. Given the near absence of other sediment sources to the lake basin, we use the mass of fine sediments deposited in the lake as a surrogate for suspended sediment yield (Mg $km^{-2}\ a^{-1}$) from the catchment. Annual yields were calculated as the mean accumulation rate obtained from the products of varve thickness and dry sediment density for all of the sampling sites. Suspended yields were adjusted for the estimated trap efficiency of Green Lake according to capacity- and sedimentation index-based empirical relations developed for reservoir systems (Verstraeten and Poesen, 2000). The median empirical estimate for trap efficiency is $95 \pm 5\%$, which accords with sediment transport estimates based on weekly to monthly suspended sediment monitoring conducted on the lake inflow and outflow from 2000 to 2003 (Schiefer, 2004).

We extended the suspended yield record back to the early 1900s and forward to 2007 by comparing the yield chronology to sediment fluxes (g $cm^{-2}\ a^{-1}$) obtained by similar varve analyses from long (>1 m) percussion cores and more recently collected gravity cores at a master coring location (Fig. 1). The master core location was identified as the site most representative of lake-wide deposition following a detailed analysis of spatial sedimentation patterns within the lake (Schiefer, 2006b). An independent estimate of suspended yield, based on conventional stream sediment sampling and rating curve development, is also available for the period 1999–2002 (Menounos et al., 2006).

2.3. Bedload

Fitzsimmons Creek deposits its bedload in an actively prograding delta at the south end of Green Lake (Fig. 1). The fan-shaped, Gilbert-type delta contains: a) horizontal topsets of imbricated gravel, coarse sand, and a small amount of woody debris; b) steeply inclined (up to ~25°) foresets of discontinuous gravels, coarse sand, and organic debris beds; and c) subhorizontal bottomsets of discontinuous sand, silt, and fine organics (Pelpola and Hickin, 2004; Schiefer, 2006a). A small portion of the suspended load may exist within the delta deposit, particularly the bottomset beds. No coarse-grained sediments associated with Fitzsimmons Creek bedload are observed beyond the bottomsets, which are limited in extent because the contemporary delta is prograding into a minor sub-basin of the lake (Schiefer, 2006a,c). Pelpola and Hickin (2004) reconstructed interannual (4- to 11-year intervals) patterns of bedload yield for the period 1947 to 1999 from vertical profiling and historical air photos. Vertical geometry of the delta was determined by bathymetric surveys and ground penetrating radar profiles. Planform change was measured from scans of historical air photos following georectification, and a volume-to-mass conversion was developed using surficial bulk samples and published densities for similar sediments elsewhere. Using an assumption that delta geometry and bulk density have remained constant recently, we extended their bedload record to 2007 through a geodetic planform survey of the delta surface.

Fitzsimmons Creek has a wandering gravel-bed morphometry (Desloges and Church, 1989) with long, relatively stable, single-thread reaches divided by short, unstable, multi-thread reaches. The only significant storage site for bedload upstream of the lake is on an alluvial fan alongside the town of Whistler (Fig. 2). Air photos show that for most of the twentieth century, the channel was stable as evidenced by vegetated islands and no observed avulsions. Engineering works initiated in the 1970s likely contributed to bank stabilization of the lower channel reaches. An event leading to high sediment yield to Green Lake and upstream bedload deposition and reworking did occur in the summer of 1991, when an unusually severe rainstorm flood reactivated a deep-seated failure in Quaternary valley fill sediments 2 km upstream of the fan, involving up to 1×10^6 m^3 of material (Mierzejewski et al., 1993). Channel aggradation and widening in response to the flood and landslide are apparent in air photos (Menounos et al., 2006; Schiefer et al., 2006). We further assessed channel morphology and width changes since 1931 from the available photographic record for Fitzsimmons Creek. Following the 1991 flood, frequent extractions of channel gravel have taken place along the alluvial fan, typically involving volumes of 2000 to 22,000 m^3 a^{-1} (Golder Associates, 2007). Because the gravel was excavated from the active bed, bedload yield may have been reduced following the extractions while bedload sediments refilled the lowered channel reaches.

2.4. Dissolved load

We periodically monitored the specific conductance of Fitzsimmons Creek water since 1999 (75 samples) to estimate solute concentrations using the following approximation: *total dissolved solids* (mg L^{-1}) = *conductance* (µS cm^{-1}) × 0.65 (Freeze and Cherry, 1979). Highest solute concentrations (>80 mg L^{-1}) were observed during low streamflows, presumably when hyporheic exchange and groundwater input were significant components of the creek's water balance. In the upper valley, high exchange flows are likely controlled by boulder and log steps along the longitudinal gradient, linking streamflow to a shallow aquifer in the thin till and limited valley fill deposits (Moore and Wondzell, 2005). The alluvial fan and thicker fill deposits in the lower valley are likely much larger aquifer bodies; however, the importance of hyporheic exchange and groundwater input along such channels of the southern Coast Mountains is uncertain.

Dissolved yield was calculated using a two-component, discharge–conductance model (Schiefer, 2004) to account for annual hysteresis observed in our data. Because the solute load also includes atmospheric and biogenic ionic constituents, this estimate of dissolved yield is only used as an upper limit for chemical denudation within the catchment. We also used water chemistry data collected by the Ministry of Environment, British Columbia, during the 1970s and 1980s (66 samples) to further assess dissolved yields. We derive a lower limit of chemical denudation by considering only the transport of dominantly non-biogenic weathering products of silicate (Na, K, Mg, Ca, SO_4, and SiO_2) following adjustment for regional atmospheric inputs (Dethier, 1986).

3. Results and discussion

3.1. Suspended sediment yield

We summarize suspended sediment yields at intervals that match the bedload record (Fig. 3). The error term in our yield estimates incorporates analytical uncertainty in laboratory analyses and unresolved spatial variability in lake sedimentation obtained from empirical modelling of depositional patterns (Schiefer, 2006b). We observe two episodes of elevated suspended yield from Fitzsimmons Creek that are superimposed on a background yield of about 100 Mg km^{-2} a^{-1} (Fig. 3). The first peak occurred following an

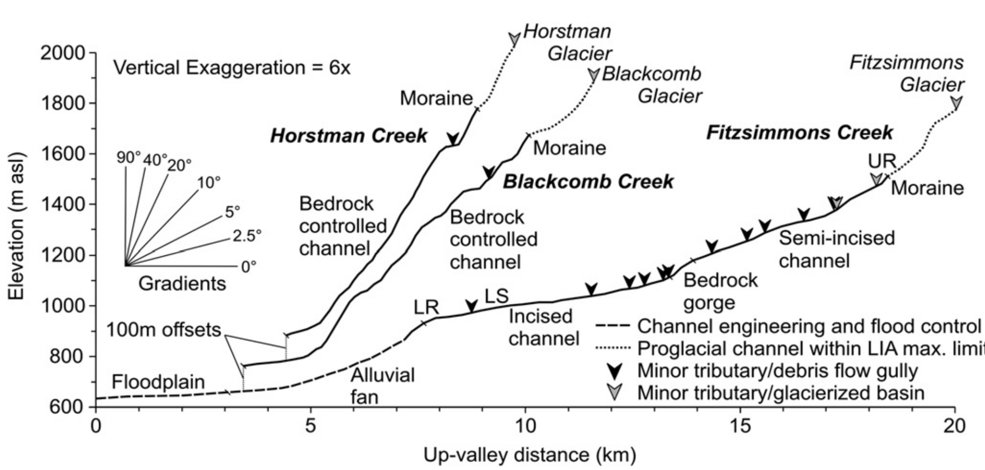

Fig. 2. Longitudinal profiles of Fitzsimmons Creek and its largest tributaries. LS marks the position of the deep-seated landslide discussed in the text. UR and LR are upper and lower reaches, respectively, of the creek where channel changes have been observed from historical air photos.

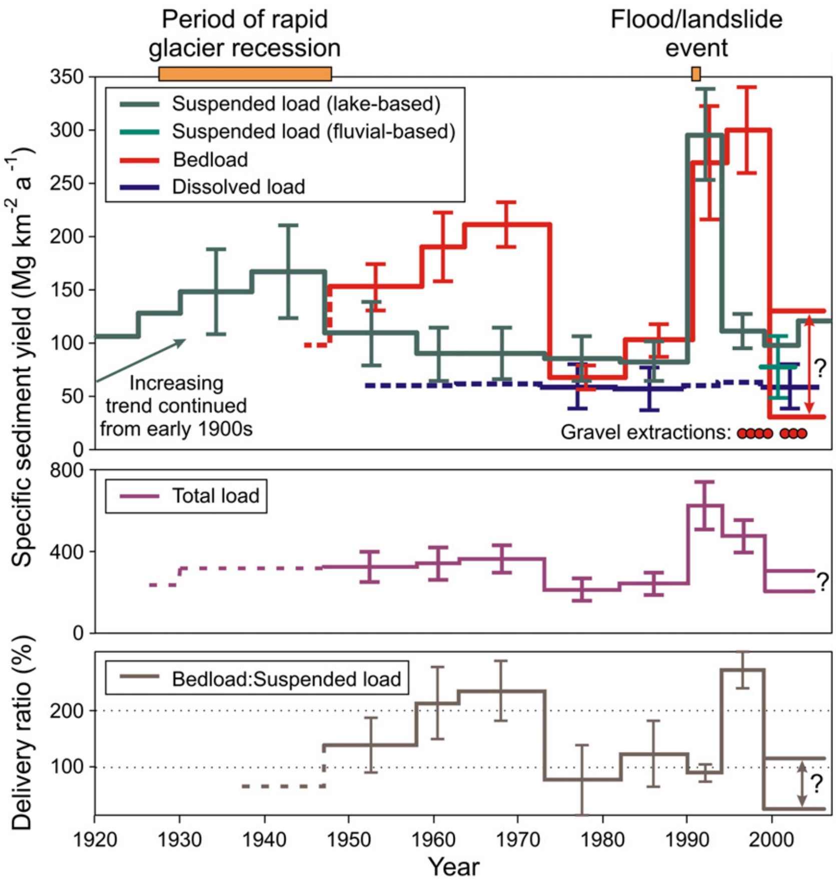

Fig. 3. Specific sediment yield records for Fitzsimmons Creek. Hatched lines indicate estimated or assumed yields. Upper and lower bedload limits for the post-1999 period indicate the potential range of gravel extraction influence based on full inclusion and exclusion of total extracted volume in the yield estimate.

increasing trend that commenced in the early 1900s and reached a high of 155 ± 45 Mg km^{-2} a^{-1} during the 1930s and early 1940s. This peak is attributed to increased sediment supply during a period of accelerated glacier retreat (Menounos, 2006; Schiefer et al., 2006)—a trend that conforms to regional observations that sediment supply from glaciogenic sources is high during periods of rapid glacier retreat (Leonard, 1997; Menounos and Clague, 2008). A second increase occurs in the early 1990s, with suspended sediment yield peaking at 295 ± 45 Mg km^{-2} a^{-1}. This second peak is related to a dramatic increase in sediment supply to the stream channel following the 1991 flood and landslide (Schiefer et al., 2006).

Suspended yield from Fitzsimmons Creek exceeds the upper envelope of fluvial loads for the western Canadian province of British Columbia (70 Mg km^{-2} a^{-1}) (Church and Slaymaker, 1989); however, it is low relative to worldwide yields reported for small montane catchments (>500 Mg km^{-2} a^{-1}) (Milliman and Syvitski, 1992). Fluvial and lake-based estimates of catchment yield are similar over the short period of overlap (Fig. 3). Uncertainty in the most recent lake-based estimates is unknown as these are based on a limited number of sediment cores from the master core location (Fig. 1). However, if sedimentation patterns remained similar to those reconstructed for the period 1930–2000 (Schiefer et al., 2006), then uncertainties would be similar to those reported for preceding decades. Fluvial-based uncertainty is a standard error obtained from the rating curve model (Menounos et al., 2006).

3.2. Bedload sediment yield

Two periods of elevated yield characterize the bedload record (Fig. 3), which we also associate with glacier recession during the early twentieth century and the 1991 flood. Reported bedload errors incorporate planform, profile, and bulk density uncertainties (Pelpola and Hickin, 2004). A railway survey in 1936 mapped the creek delta at a similar position as observed in 1947 air photos. Unfortunately, the errors associated with this survey are unknown, so delta progradation prior to 1947 is uncertain. Bedload increased from the 1950s to the early 1970s, peaking at 210 ± 20 Mg km^{-2} a^{-1}. This trend may be related to glacier recession during the 1930s and early 1940s when glaciogenic sediments became important sediment sources for Fitzsimmons Creek. The lag between glacier retreat and heightened bedload flux may reflect the slower movement of bedload through the fluvial system compared to silts and clays. An average transport velocity of 0.3 to 0.6 km a^{-1}, necessary to explain a three-decade lag in bedload transfer from proglacial sources 9 to 18 km upstream (Fig. 2), is within the observed range for gravel-bed rivers (Hassan et al., 1992). We also note that greater freshet floods observed in local hydrometric records for those decades (about a 5% mean daily discharge increase seasonally) may further account for elevated bedload yield between the 1950s and 1970s because of increased transport capacity coinciding with increased sediment supply. Enhanced bedload flux is unlikely to have resulted from land use as these activities took place on gentle, ungullied slopes that are largely decoupled from the drainage network. The absence of elevated suspended sediment yield during or following years when land use occurred supports our suspicion that changes in yield from human activity was minimal.

Bedload reached a second peak shortly after 1990 when it abruptly increased to a maximum of 300 ± 40 Mg km^{-2} a^{-1} (Fig. 3). This peak followed a period of low bedload delivery during the late 1970s and 1980s, with a minimum yield of 70 ± 10 Mg km^{-2} a^{-1}. Like the suspended yield record, elevated bedload during the 1990s is attributed to the extreme rainstorm event in 1991 (Pelpola and Hickin, 2004).

Unlike the earlier period, lag between the time of sediment mobilization and heightened bedload yield is not apparent. Analysis of air photos reveals that a large volume of valley fill sediment about 1 to 2 km upstream of the alluvial fan was delivered to the channel during the rainstorm. The recent construction of flood control structures has also increased channel confinement and decreased bedload storage potential along lower reaches of Fitzsimmons Creek. Increased bedload delivery continued through the late 1990s, as unstable colluvium and alluvium from lower valley reaches likely continued to be major sediment sources.

Surveyed delta growth for the period 1999 to 2007 suggests a bedload yield of only 30 Mg km^{-2} a^{-1}, assuming a consistent longitudinal geometry and bulk density to that reported by Pelpola and Hickin (2004). Gravel extractions from the creek probably suppressed delta progradation as bedload flux for that period would be 130 Mg km^{-2} a^{-1} if extraction volumes are added to the yield (assuming a density of 1.7 Mg m^{-3}). Actual bedload yield is probably between 30 and 130 Mg km^{-2} a^{-1}, however, as some of the extracted sediment was likely inactive valley fill.

Channel changes observed in the air photo record support the bedload sediment source and transport interpretations described above. Near the Little Ice Age terminal moraine (UR in Figs. 1 and 2), Fitzsimmons Creek widened and became multithreaded during the 1930s and early 1940s. This planform change coincides with a period when glaciers in the watershed rapidly retreated, heightening the flux of glaciogenic sediments to the channel system. Changes in downstream channel morphology and sediment yield resulting from recent glacial recession may be diminished because decreasing ice cover in the catchment may curtail sediment supply and melt-water transport capacity. An undisturbed forest canopy obscures lower channel reaches during most of the twentieth century. The deep-seated landslide initiated by the 1991 rainstorm and subsequent lateral erosion of the river along a lower reach of Fitzsimmons Creek (LR in Figs. 1 and 2) explain a notable channel widening observed in air photos of the late twentieth century (Mierzejewski et al., 1993; Schiefer et al., 2006).

3.3. Dissolved sediment yield

Conductivity measurements for the 1970s and 1980s fall within the range of the recent monitoring data with little interannual variability. Therefore, decadal scale estimates of dissolved yield are assumed to primarily vary as a function of total discharge, which has been approximated for the Fitzsimmons Creek catchment from regional records (Schiefer et al., 2006). Partial dissolved loads, calculated from the transport of major ions associated with silicate weathering, indicate that the denudational fraction of the solute load may be up to 50% below the conductance-based approximation of total dissolved load. Because discharge variability has been relatively low over recent decades (<9% volume variation decadally) compared to suspended and bedload yield variations, we estimate that dissolved yield associated with chemical weathering to be relatively stable at 60 ± 20 Mg km^{-2} a^{-1} since the mid-twentieth century (Fig. 3), a magnitude similar to that reported for intrusive terrain elsewhere in the Pacific Northwest (Dethier, 1986). These data further suggest that dissolved load, although commonly disregarded in montane denudation studies in noncarbonate regions, can represent a significant fraction of total sediment yield. Low interannual variability in the dissolved load relative to the suspended load is consistent with the results from other studies of sediment yield from montane catchments (Caine, 2004; Gislason et al., 2006; Beylich and Kneisel, 2009).

3.4. Total sediment yield

Integrated over the last 50 years, total sediment yield averaged 320 ± 40 Mg km^{-2} a^{-1}. This rate reflects both primary denudation and secondary remobilization of Quaternary deposits from the catchment. Over the period of study, total yield comprised ~35% suspended load, 50% bedload, and 15% dissolved load. Glacier retreat and the 1991 rainstorm mobilized comparable volumes of total clastic sediment, but transfer response times differed accordingly. Total yield clearly shows the influence of the rainstorm flood through the 1990s (Fig. 3), but the signal of glacial recession earlier in the record is subdued because of the asynchronous delivery of suspended load and bedload. Because of these differences, the proportion of bedload to suspended load has varied by over a factor of three, ranging from ~80 to 270%. Sediment flux associated with the transfer of poorly-sorted, glaciogenic sediment to Fitzsimmons Creek during the early twentieth century may have involved similar total quantities of suspended load and bedload sediment. Sediment outflow associated with the extreme 1991 flood and landslide involved a greater total quantity of bedload sediment, which may reflect the inclusion of previously sorted and abraded sediment within the remobilized valley fill. The extent to which source distribution and sedimentology may ultimately constrain long-term ratios between sediment delivery modes remains uncertain.

Our results imply that reported bedload-to-suspended load ratios, typically in the range of ~2 to 30% (Lane and Borland, 1951; Gregory and Walling, 1973; Caine, 2004; Babiński, 2005), may significantly underestimate bedload from some montane catchments. Others have noted similar deficiencies in the use of these delivery mode ratios for catchments an order of magnitude smaller and larger than that of Fitzsimmons Creek (Duck and McManus, 1994; Pratt-Sitaula et al., 2007). Our study also indicates that the bedload-to-suspended load ratio can markedly fluctuate over decadal timescales. Our results differ from those of Loso et al. (2004) for a heavily glacierized catchment in southern Alaska, where the bedload-to-suspended load ratio has been relatively stable over similar timescales. This stable pattern of delivery observed by Loso et al. (2004) could reflect the dominance of glacier erosion in that catchment with little potential for transient sediment storage.

4. Conclusions

The variable total magnitude and fluctuating load ratios of sediments exported from Fitzsimmons Creek typify the complex patterns of sediment supply and storage that are common for mountain drainage basins. Contrary to the common assumption of a constant ratio, we observed substantial interannual and interdecadal variability in the magnitude of individual load fractions because of lag and duration differences between the clastic yield components following climatic shifts and extreme hydrological events. Sediment monitoring programs may be insufficient to assess long-term catchment response to such hydroclimatic forcings, particularly in dynamic, montane environments. Extrapolations based on short-term monitoring may lead to biased projections of longer term yields and delivery mode ratios if potential variations in sediment availability and transitory sediment storage in the channel are not carefully considered. Limitations of conventional monitoring can be reduced by integrating studies of downstream sedimentation and other historical proxies of sediment transfer.

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