Long-term bed load transport rate based on aerial-photo and ground penetrating radar surveys of fan-delta growth, Coast Mountains, British Columbia

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Received 29 August 2002; received in revised form 10 February 2003; accepted 28 February 2003

Abstract

Sequential aerial photography, sonar bathymetry, ground-penetrating radar (GPR), and sediment sampling and analysis provide the basis for calculating the volumetric and mass rate of progradation of the delta of Fitzsimmons Creek, a steep, high-energy, debris-flow-dominated channel draining about 100 km\textsuperscript{2} of the southern Coast Mountains of British Columbia. Fitzsimmons Creek is typical of small mountain rivers in the region. GPR imaging is used to define the pre-depositional morphology of the receiving basin, a technique that improves the accuracy of the volumetric survey. The 52-year record (1947–1999) of progradation yielded an average annual volumetric transport rate of $1.00 \pm 0.16 \times 10^4$ m\textsuperscript{3} year\textsuperscript{-1} for bed load, corresponding to a mass transport rate of $1.60 \pm 0.28 \times 10^4$ Mg year\textsuperscript{-1}. Bed load yields are consistent with those obtained in hydrogeomorphically similar basins in the region and elsewhere. Decade-based annual rates, which vary from $0.64 \pm 0.11 \times 10^4$ to $2.85 \pm 0.38 \times 10^4$ Mg year\textsuperscript{-1}, provide poor estimates of the 52-year average. Indeed, the 52-year record may also not be long enough to fully integrate the significant fluctuations in the sediment efflux from Fitzsimmons Creek. The methodology proposed in this paper can be transferred to other comparable mountain environments worldwide.

Keywords: Delta progradation; Bed load transport; Sediment yield; Ground-penetrating radar

1. Introduction

1.1. The problem

In coastal British Columbia, the regime of sediment transport in small, high-energy rivers draining the mountains is known to be extremely erratic in the short term, but long-term sediment-transport regime is poorly understood. Most current research on bed load transport highlights the inadequacy of bed load transport formulae to provide reliable estimates of sediment transfer (Gomez and Church, 1989; Martin and Church, 2000). Bed load transport formulae are based largely on data from nonalpine environments, and the problem of predicting bed load transport from these formulae therefore becomes most apparent in mountain channels for which they were not developed (Parker et al., 1982). The problem lies in the inability of conventional measurement techniques

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and formulae to accurately characterize a system, which is both spatially and temporally variable in the extreme.

Variability in sediment transport in rivers is evident over a wide range of timescale, from minutes to years, much of it reflecting hydrologic forcing conditioned by seasonal climatic regimes. Interannual fluctuations are driven by cycles and intermittency in atmospheric circulation and associated storm patterns coupled with sediment availability. Sediment transport in rivers draining mountainous terrain is particularly difficult to assess because the amount of sediment carried by small but powerful steep mountain streams probably is limited by sediment supply rather than by hydraulics (Galay et al., 1998). Exacerbating this already difficult problem is the fact that sediment supply involves very complex slope–channel coupling that often leads to sediment supply being dominated by debris-flow events that have a highly irregular pattern of occurrence and intensity over a wide range of timescales. Clearly, the sediment transported during debris-flow events must be included in sediment transport estimates if such measurements are to be meaningful. Yet even the most intense in-stream sediment-sampling program will miss such infrequent catastrophic sediment pulses. The point is rather academic in the case of British Columbia, however, because within-channel measurements of sediment transport in mountain rivers are rare and, if they exist at all, are not continuous for any length of time. Almost all sediment survey records on BC rivers are of < 10-year duration, rendering it impossible to know whether these short-term records integrate sediment transport variability occurring at decadal or longer timescales.

British Columbia is not unique in this regard. Elsewhere, long-term records of bed load transport rate in mountain catchments also are rare. These data are very important, however, to understanding the process geomorphology of mountain environments and vital to the design of engineering structures in mountain villages and alpine transportation corridors.

1.2. A solution

An alternative approach to measuring fluvial sediment transport rate directly is to examine changes in the geomorphology of fluvial features constructed by (or supplying) the sediment in transport (Martin and Church, 1995; Ashmore and Church, 1998; Ham and Church, 2000). Two previous studies in the region have documented rates of sediment efflux from Lilooett River (Gilbert, 1975) and Squamish River (Hickin, 1989) based on delta progradation rates. The principal advantages of this type of “reservoir” survey is that it completely avoids the instrumentation problems of within-channel sediment-sampling, and the survey differing over many decades yields sediment volumes that fully integrate the temporal variability within the survey period. It has been widely applied elsewhere (for examples, see Vanoni, 1975; Rickenmann, 1997; Verstraeten and Poesen, 2000) to estimate sediment yields, although the technique is not without limitations.

The principal challenges facing the application of this method are that the geomorphic change has to be measurable and it has to be subject to some sort of dating control. Repeated ground surveys over decades of changes in built reservoirs can provide accurate sediment volumes, but deriving the same quality of information from photo and map records of changes in natural features is more problematic. For example, although the planimetric changes in rapidly prograding deltas may be easily reconstructed from sequential aerial photography, the precise shape of the buried surface of the receiving basin, and therefore the three-dimensional form of the accumulating sediment body, is more difficult to establish with precision. Recent developments in the application of geophysical techniques to these types of survey problems, however, have removed much of the uncertainty about the vertical dimensions of such sediment bodies (Jol and Smith, 1991). Shallow subsurface imaging by ground-penetrating radar (GPR) has been particularly successful in geomorphic applications (Beres et al., 1999).

There are two primary aims of this study. The first is to present a case study illustrating the utility of combining sequential aerial photography, echo-sounding, and GPR surveys in reconstructing delta progradation in small alpine lakes. This study is the first to use GPR imaging to define the pre-depositional morphology of the receiving basin, a technique that improves the accuracy of the survey and derived bed load transport rates. The second aim is to derive
from this geomorphic survey a long-term (50 years) bed load transport rate for a small, steep channel (Fitzsimmons Creek) in the rugged mountains of coastal British Columbia. Fitzsimmons Creek is typical of small energetic rivers on the southern Coast Mountains and is regarded as being representative of those in the region.

### 2. The field site and regional setting

Fitzsimmons Creek is located in Whistler, British Columbia, ~120 km north of Vancouver within the Coast Mountains of the Canadian Cordillera (Fig. 1). The study area encompasses the lower reaches of Fitzsimmons Creek where it enters the receiving basin, Green Lake. Here, Fitzsimmons Creek forms a fan delta, largely composed of sand and gravel, at the southern end of Green Lake. Wave action on the lake has an insignificant effect on the coarse sediments forming the fan delta. The surface of the feature has little relief and is characterized by multiple distributary channels (Fig. 2).

Fitzsimmons Creek drains ~100 km² within a well-defined valley in which the channel drops ~2 km over a distance of 18 km (Woods, 1993). Along the alluvial fan, the creek is a wandering gravel-bed river with stable vegetated islands separating multiple channels 5–20 m in width at bankfull flow. Channel gradient ranges between 1% and 3%. In the lower reaches, the main channel is naturally unstable but recently short reaches have been engineered to maintain the existing single channel of the gravel-bed river.

The Fitzsimmons Creek catchment was heavily glaciated during the Pleistocene. The main valley has been free of ice for the last 10,000 years although small headwater glaciers persist in the uppermost

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**Fig. 1.** Location of study area in southwestern British Columbia.
valley today. Lateral moraines border the small glaciers and extend <1 km downvalley, left behind by recent glacier recession. Sediment is supplied to the river headwaters from veneers of till and colluvial sediments resting on the very steep exposed surfaces of relatively unweathered dioritic plutons. The thin unconsolidated sediment veneers commonly fail during intense rainstorms, generating debris flows including one documented event in 1991 that reached the fan delta.

Although the catchment is largely forested, forest cover is absent along snow-avalanche tracks, in the high alpine zone, and in the developed area of the lower valley. Terraces in the mid-valley were commercially logged between 1959 and 1963.

Average annual rainfall at the mouth of Fitzsimmons Creek is 801 mm, and average annual snowfall is 6574 mm deep (Environment Canada, 1981). The hydrology of the creek is characterized by two peak flow events associated with spring snowmelt and frontal fall rainstorms (Fig. 3). The annual average daily discharge of Fitzsimmons Creek is 4.45 m$^{3}$ s$^{-1}$ at the Water Survey of Canada gaging station in Whistler Village based on existing periodic discharge data from 1994 through 1999.

Fig. 2. Aerial view of the fan-delta illustrating the network of distributary channels.

Fig. 3. Annual daily hydrograph for 1995 showing two peak discharge events (data from Water Survey of Canada, 1999).
1999. Extreme floods of much greater magnitude present a common hazard; the most recent damaging event of $130 \text{ m}^3 \text{s}^{-1}$ occurred in August 1991.

3. Field methods and data analysis

3.1. Some definitions

Sediment is delivered to Fitzsimmons Creek delta through a set of mixed gravel and sand-bed distributary channels. In all but extreme discharges, sediment is transported as bed load and is deposited on the delta front. At high discharges, silt and clay are carried in suspension beyond the delta, forming a jet-like plume that eventually dissipates in the distal environment of the lake. For the sake of developing the present discussion, the sediment forming the delta is assumed to be primarily derived from the bed material load of Fitzsimmons Creek and that sediment volume calculations relate to the rate of bed material transport. The total sediment efflux, however, obviously must include the silt and clay moved as suspended sediment, but this component is not the subject of the present study.

3.2. Measurements

In order to measure the incremental volumes accumulating in the delta of Fitzsimmons Creek, three primary measurements must be made: the surface area of the depositional increment, the thickness of the depositional increment, and the time interval of deposition. Conversion of the volumetric rate of sediment efflux to a mass rate of transport also requires measurement of the bulk density of the delta sediments. Error statements specified for the primary survey measurements (length and sample bulk density) reflect estimates of measurement accuracy and those for derived results (area, volume, average bulk density, and sediment transport rate) reflect propagation of errors in the calculations.

3.3. The planform increments

The delta planform increments were determined by differencing air-photo images of the fan taken at known dates. British Columbia government aerial photographs (1947, 1958, 1963, 1973, 1982, 1990, 1994) were obtained from MAPS BC, the Ministry of Environment, Lands and Parks Survey and Resource Mapping Branch. The Ministry of Environment, Lands and Parks, Water Resources Branch, provided the most recent aerial photograph (1999) to extend the sequence. Sequential aerial photographs from 1958 to 1994 were enlarged from original negative film while the 1947 and 1999 aerial photographs were enlarged using a flatbed scanner (300 dpi) and printed onto photographic quality paper at the same scale. Scales of enlarged aerial photographs ranged from 1:2850 to 1:4300 and were calculated from the ratio of distances between landmarks on each photo and the true distance between landmarks surveyed in the field.

The margin of the fan delta was taken as the planform boundary because it was clearly visible in aerial photograph enlargements. The margin was measurable within $\pm 1 \text{ m}$ due to distinct colour changes between the sediment of the delta and the water of the lake. Lake levels fluctuate within $\pm 1 \text{ m}$ between winter and spring runoff events. Aerial photographs were taken in the late fall. Any errors associated with fluctuating lake levels are assumed to be within the planform measurement error. The British Columbia Rail bridge crossing at Fitzsimmons Creek provided an ideal primary reference point for baseline measurements on all aerial photography. Therefore, a simple mapping and measuring procedure was developed based on this clearly visible base point. Distance from the primary base point to the margin of the fan delta was measured along a radial grid fanned outward at 7.5° intervals. Measured distances from eight successive aerial photographs were transferred to a base map showing the advance of the fan delta margin over the period of analysis (1947–1999) at a scale of 1:2000. Error associated with distances measured from aerial photographs was $\pm 1 \text{ m}$. Successive fan delta margin locations plotted on a 1:2000 base map were transferred to a GIS program (Arc INFO 3.1) using a standard digitizer tablet. Differences in the areas between the fan delta margins from sequential aerial photographs were calculated in Arc View (version 3.1).

3.4. The vertical dimension

A bathymetric survey of the receiving basin, Green Lake, was measured along a radial grid convergent on a
base point on the modern delta front with the objective of estimating the thickness of sediment accumulated in the fan delta. Bathymetry data were collected with a Lowrance low-frequency echo sounder (25 kHz) and plotter mounted in a powered Zodiac inflatable boat. A transect was conducted in the direction of river flow and fan delta progradation. Nine radial transects, centred on the primary transect, were fanned out at 15° intervals relative to a base marker (Fig. 4). Depth profiles were spatially located with respect to the margin of the fan delta using a laser range finder and on-shore survey markers. Depths measured along bathymetric transects were generalized as lake-bottom contours plotted on a 1:2000 map.

In the two previous delta-progradation studies in the region, the shape of the receiving basin was either known from sequential bathymetry (Hickin, 1989) or it was assumed that the delta was advancing onto an essentially horizontal planar lake bed (Gilbert, 1975). Although the Fitzsimmons Creek receiving basin is relatively small, there is sufficiently variable offshore depth indicated by the bathymetry to cause some concern about the validity of assuming a simple form for the underlying lake bed. For this reason, the internal architecture and sub-surface boundaries of the delta were imaged by a ground-penetrating radar (GPR) survey.

All GPR data were collected with Simon Fraser University’s 400 V Sensors and Software pulseEKKO™ IV radar system. The 50-MHz antennae were used with a 2-m spacing and moved broadside perpendicular at 0.5-min intervals along transects marked with a fibreglass tape measure. The time window and sampling interval were set at 1000 ns and 1600 ps, respectively, and traces were stacked 64 times. GPR signal processing consisted of automatic gain control (AGC), which amplified the weaker reflections at depth. GPR transects were positioned so that all major lobes of the fan delta were surveyed (Fig. 4).

### 3.5. Sediment bulk density

A volume-to-mass conversion was calculated from the bulk density of the sediment. Sediment on the delta surface was sampled by a custom-built 20 × 20 × 20-cm cube sampler, dimensions which exceeded those of the largest clast in the sample area. Preparation of each sample site involved excavation to the depth of the largest clast within the sample location (after Wolman, 1954). The cube sampler, placed open-side down onto the excavated surface, was pressed into the subsurface until it was completely below grade, then extracted and turned open-side up with the sediment held intact. Excess sediment was sheared off at the sampler rim using a trowel. Samples were returned to the laboratory for drying, weighing, and grain-size analysis based on sieve shaker sorting. The bulk density of sediments at depth was estimated on the basis of the assumed grain-size characteristics and published densities for similar sediments elsewhere (Lane and Koelzer, 1953). An average bulk density for the full sediment column, obtained by a weighting formula based on the internal architecture revealed by the GPR surveys, is described in the results to follow.

### 4. Results and interpretation

The map in Fig. 5 shows the advance of the delta front over the photo period of 52 years. Measurable differences in the planimetric development of the fan...
delta over photo periods (ranging from 4 to 11 years) are clearly apparent. As Fig. 4 implies, the 10-year period between 1963 and 1973 appears to have produced the greatest delta planform growth, while the 9-year period between 1973 and 1982 appears to have experienced the least delta progradation.

Bathymetric profiles along 10 transects indicate basin depths at the toe of the delta ranging from 10 to 18 ± 0.5 m. Depths from five of these bathymetric profiles reveal a shallow basal area in the region immediately NW of the study site, while the deepest area is to the NE of the fan delta margin. The bathymetric profile in Fig. 6 reveals the steeply inclined delta front, close to the fan delta margin, grading to less steeply inclined sediment and to subhorizontal strata. The transition from steeply inclined sediment to less inclined sediment occurs at a depth of 12 m. The slope of the steepest delta front approaches 25°.

Ground-penetrating radar profiles display EM-wave, two-way travel times of 140–260 ns to the paleolake bottom, corresponding to depths ranging between 10 and 18 ± 0.5 m from 12 GPR transects. The depth of GPR signal penetration is limited by the thickness of fan delta sediments, which overlie basal lacustrine sediments through which the GPR pulse could not be transmitted. GPR profiles revealed the presence of three distinct delta facies: horizontal topsets, steeply inclined foresets, and nearly horizontal bottomsets. Fig. 7 illustrates topset facies, horizontal in nature and ranging in thickness from 3 to 4 m. Foreset facies in the apparent dip direction range in thickness from 6 to 8 m. Sub-horizontal bottomset facies range in thickness from 2 to 5 m. The lower-bounding surface was inferred as the depth which GPR signal attenuation occurred, the contact point between coarse fluviatile sediments (bed-material load) and finer lacustrine sediments (suspended sediment load) of silt and clay.

The bulk density of near-surface sediment samples is $1.79 \times 10^3$ kg m$^{-3}$ based on the average mass of 41 surface sediment samples extracted by the cube sampler. This bulk density value has been assigned to the topset bed component of the sediment pile. A
Fig. 7. (A) Ground-penetrating radar profile in the direction of dip. (B) Interpreted boundaries showing three distinct radar facies.
bulk density of $1.58 \times 10^3$ kg m$^{-3}$ has been assigned to the foreset component of the sediment pile based on literature reviews of comparative bulk densities in neighbouring rivers such as the Lillooet River ($1.4 \times 10^3$ kg m$^{-3}$; Gilbert, 1975) and the Squamish River ($1.45 \times 10^3$ kg m$^{-3}$; Hickin, 1989). These values were averaged with estimates from U.S. Geological Survey (USGS) tables of subaqueous sand and gravel bulk density (Vanoni, 1975). A bulk density of $1.25 \times 10^3$ kg m$^{-3}$ has been assigned to the bottomset component of the sediment pile based on USGS guidelines for subaqueous sediment (Vanoni, 1975).

The bottomsets, as defined by the radar profiles (see Fig. 7), have been included in the calculation of bed material load because they likely contain an abundant amount of sand and gravel. This interpretation is based on geomorphology and radar penetration behaviour. The high angle of the fan delta front likely promotes slope failure and grain avalanching to the bottomsets. Furthermore, bottomset beds are clearly visible in GPR surveys; and because radar does not penetrate silt and clay sediment effectively, they point to coarser grains being present in the bottomset beds.

The average bulk density for the fan delta sediment body is based on the weighted average of each of the three components. Weighting is based on the 1:2.5:0.5 ratio of the topset, foreset, and bottomset thickness evident in the GPR profiles. The result of this integration is a calculated average bulk density for the entire fan delta sediment body of approximately $1.60 \pm 0.10 \times 10^3$ kg m$^{-3}$, the value adopted here for all volume-to-mass conversions.

A paleolake contour model of the receiving basin overlain by the fan delta was constructed based on depth interpretations from a combination of bathymetric and GPR surveys (Fig. 8). The purpose of the paleolake contour model is to provide average depth estimates in areas not measured by bathymetric or GPR profiling. Volume estimates were based on a combination of depth estimates from the paleolake contour model and GIS-based area estimates of planform differences.

The variability associated with average annual bed material transport rates over sequential periods of measurement is illustrated in Fig. 9. Average bed material transport rates range from $0.64 \pm 0.11 \times 10^4$ to $2.85 \pm 0.38 \times 10^4$ Mg year$^{-1}$. The total mass of bed material load in the fan delta for the 52-year period is $8.35 \pm 1.44 \times 10^5$ Mg, corresponding to an average annual transport rate of $1.60 \pm 0.28 \times 10^4$ Mg year$^{-1}$ ($1.0 \pm 0.16 \times 10^4$ m$^3$ year$^{-1}$).

Allowing for the overlapping error bars, a weak upward trend in the average annual bed-material efflux is suggested by the data in Fig. 9. The average rate increased by $0.56 \times 10^4$ Mg year$^{-1}$ between 1947 and 1973. After 1973, a sharp decline in the rate to a comparatively low average bed material transport rate occurred in the 1973–1982 survey period. Between 1982 and 1994 the rate again increased; the highest rates in the 52-year period occurred in the most recent decade, 1990–1999.

The average sediment transport rate increased signifi-

5. Discussion

The total volume of sediment accumulated in the fan delta in the 52-year period of this study is $5.22 \pm 0.31 \times 10^5$ m$^3$ and has not been adjusted for compaction. The coarse-grained (largely clast-supported) fan delta in this study formed over a 52-year period, and we assume that any correction for compaction of sediment in the fan delta likely would be small and within the margin of volume-measurement error.

Considerable temporal variability of the decadal averages of bed material transport is evident over the 52-year record with estimates ranging from a low of $0.64 \pm 0.11 \times 10^4$ to a high of $2.85 \pm 0.38 \times 10^4$ Mg year$^{-1}$. The results reveal that decadal averages of bed material transport rate in this alpine environment varies, by a factor of about 5 over the five-decade record. Causes of the variation of sediment transport rates are not known with certainty, but both natural and anthropogenic factors clearly are involved.

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The greatest increase in average annual bed material transport rate is evident in the periods 1982–1990 and again in 1990–1994. The cause of the first phase of accelerating transport rate is not known, but the most likely explanation for the second is a major flood and debris-flow event (Ward and Skermer, 1992; Brown, 1993) that occurred in August 1991. The debris flow originated $\sim 7$ km upstream in the steep, confined valley above the alluvial fan and transported gravel-sized sediment to the distal fan and beyond to the fan delta forming in Green Lake. The effect of these debris-flow events on sediment supply to the river channel, however, is complex and apparently staged, involving phases of deposition and remobilization of sediment. Although no documented flood event occurred between 1994 and 1999, this period exhibits the greatest average annual transport rate. This result may be explained by moderate flows remobilizing the 1991 debris-flow sediment stored within the channel. The sediment supply for the fan delta in this study is the alluvial fan. Coarse sediment is largely stored along the alluvial fan of Fitzsimmons Creek, predominantly confined along and within the existing channel. Observations of the channel along its entire length indicate sediment is readily available, but transport of coarse material is discharge limited. The highest transport rate may be explained by a combination of high discharges in the later part of the record and the availability of sediment directly upstream from the fan delta. Variation in discharge alone, however, does not explain the variation in the transport rate of bed material in this system. Ashmore and Church (1998) stated that there may be influences other than gross hydraulic conditions on the mean bed material transport rate, such as sediment supply, controls also noted by Galay et al. (1998) and Rickenmann (1997) among others. In the case of Fitzsimmons Creek, land use (such as construction of parking lots, residences, and engineering of the creek channel) during the last decade may have increased peak discharges and stream power and thus the transport of additional coarse sediment (Pizzuto et al., 2000).

The average bed material transport rate based on decadal records is highly variable (by a factor of about 5). These statistics dictate caution when using even 10-year records of direct measurement to estimate the long-term (50 years) sediment-transport rate in these mountain channels. Indeed, the data in Fig. 9 do not indicate with certainty whether the 50-year record is long enough to fully integrate the significant fluctuations in the sediment efflux from Fitzsimmons Creek. Increasing the length of record beyond 50 years may also not achieve this end because fluctuations in climate may begin to be a factor beyond this timescale. This elusiveness of a representative record likely is exacerbated in basins smaller than Fitzsimmons Creek since the character of perturbations in the bed load transport record likely are dependent on the spatial scale.

Because Fitzsimmons Creek fan probably consists largely of gravel and coarse sand, the bed load transport rate for Fitzsimmons Creek can be compared with the gravel transport rates obtained for other rivers along the western coast of North America and similar regions elsewhere. As noted in Introduction, however, data based on this duration of record (50 years) and type (bed load yield alone) are rare, although many short-term records of total sediment yield have been published for various rivers in recent years (Wohl, 2000).
The bed load/drainage area relation shown in Fig. 10 is based on several datasets for regions with broadly similar hydrogeomorphology to that encountered in the Coast Mountains of British Columbia. Data for the Pacific Northwest have been derived from the Wynoochee, Cache, Dungeness, and Skykomish Rivers in coastal Oregon and Washington (assembled by Collins and Dunne, 1990, and reported in Galay et al., 1998) and from data for rivers in British Columbia (Chilliwack, Lillooet, Mamquam, and Cowichan). The set is supplemented by data from Alaskan rivers (Susitna and Yentna) and the Manawatu River in New Zealand. To these examples, with drainage areas between 322 and 19,400 km², have been added data from smaller catchments (1.3–381 km²) in central and northern Idaho (from Whiting et al., 1999) and very small catchments (< 2.0 km²) reported by Rickenmann (1997) for rivers in the Swiss Alps.

The plot of annual gravel load in Fig. 10 shows a rough scaling with drainage area and indicates that the average annual bed load yield of Fitzsimmons Creek is consistent with the general trend of data and clearly forms part of the Pacific Northwest group of channels. Fig. 10 also displays the several orders of magnitude scatter in bed load yield that many observers note as being typical of these mountain rivers (Wohl, 2000). The New Zealand and Alaskan river data extend the Pacific Northwest array to large drainage areas, but the Idaho data generally plot well below this trend. The low bed load yields could reflect less abundant supply of sediment (Whiting et al., 1999), but it may also simply reflect the short records that fortuitously are associated with the lowest yields. Noteworthy is the fact that the Idaho data point based on the longest record (54 years) also represents the largest yield and the one most consistent with the Fitzsimmons Creek data. The very small Swiss basins have several decades of record based on sediment trap or retention basin data and seem to form a linear extension of the Pacific Northwest data to very small catchments, although undersupply of sediment to these hydrologically vigorous streams is also evident in the field (Rickenmann, 1997).

The data in Fig. 10 also support a conjecture by Galay et al. (1998) that typical bed load sediment yield in the mountainous environment of the Pacific Northwest sets a lower drainage area limit of about 100 km² for the catchment size yielding the minimum annual load of gravel (~ 10,000 m³ year⁻¹) for economical extraction. Headwater streams in Idaho of about the same size, however, have bed load yields two orders of magnitude lower.

The 10,000 m³ of average annual bed material efflux recorded in the fan delta sediment record is only part of the total sediment influx of material transported beyond the mouth of the river into Green Lake and beyond. Fitzsimmons Creek is by far the most significant source of suspended sediment supplied to Green Lake, however; and a recent lake sediment survey (Menounos, 2002) suggests that average annual suspended-sediment influx to Green Lake is about 20,000 Mg year⁻¹. Thus, bed load appears to be a much higher proportion of the total sediment load (perhaps one third to half the total) than the 5–10% taken as normal for larger rivers (Gurnell, 1987). This observation is consistent with many others that recognize the relative importance of bed load in the total sediment yield carried by small mountain streams (for examples, see Mizutani, 1987; Gurnell, 1987; Bezinge, 1987).

6. Conclusion

This study demonstrates the utility of combining sequential aerial photography, bathymetry, and GPR
surveys to reconstruct the history of volumetric progradation and mass rate of sediment supply to the small natural delta of Fitzsimmons Creek prograding into Green Lake near Whistler, BC. Because such lake fan-deltas are common in alpine valleys, this technique has considerable promise as a viable alternative to direct monitoring for determining the long-term bed load transport rates of comparable mountain rivers worldwide.

In Fitzsimmons Creek, the 52-year record of progradation yields an average annual volumetric transport rate of $1.0 \pm 0.16 \times 10^4 \text{ m}^3 \text{ year}^{-1}$ for bed load, corresponding to a mass transport rate of $1.60 \pm 0.28 \times 10^4 \text{ Mg year}^{-1}$. These bed load yields are consistent with those obtained in hydrogeomorphically similar basins elsewhere in the region.

As also observed elsewhere, the average annual bed material transport rate for a river draining a steep alpine environment with an abundant sediment supply is highly variable. Average annual transport rates based on decades vary by an order of magnitude. The greatest annual transport rate was measured in the decade following a major flood and debris flow event, most likely explained by a combination of the increased availability of sediment in the alluvial fan immediately upstream of the fan delta and subsequent discharges capable of mobilizing sand and gravel-sized sediment.

The 52-year record of bed load transport on Fitzsimmons Creek shows clearly that a decade is not long enough for determining a stable, long-term, average bed load transport rate. Furthermore, the full 52-year record may not be long enough to fully integrate the flood/debris flow regime operating there. In this sensibly homogeneous mountain environment, temporal variability in the long-term bed load transport exhibited by this basin likely is similar to that in other basins in the region. Furthermore, the study suggests the possibility of similar behaviour in other comparable basins in mountain regions worldwide.

Acknowledgements

This paper reports work completed by the first author at Simon Fraser University as an MS thesis (Pelpola, 2001). It forms part of a project on the morphodynamics of British Columbian rivers funded by Simon Fraser University and by the Natural Sciences and Engineering Research Council of Canada.

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