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Nested temporal suspended sediment yields, Green Lake Basin, British Columbia, Canada

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Abstract

Suspended sediment yield was determined for a mountain watershed by calculating the volume of sediment stored in the watershed's outlet lake basin and monitoring sediment transport for the lake's primary inflow. Lake-based yields for the 1931–2001 period (0.21 ± 0.03 Mg km^{-2} day^{-1}) are 10% higher than estimates for the last 3000 years (0.19 ± 0.05 Mg km^{-2} day^{-1}). Fluvial (0.24 ± 0.08 Mg km^{-2} day^{-1}) and lake-based yields (ca. 0.21 ± 0.07 Mg km^{-2} day^{-1}) are comparable over the period of overlap (1999–2001). Persistence in the long-term yield record is dominated by low frequency (century to decadal) periodicity. This periodicity is shown to inflate the standard error of the sediment yield estimate for the basin. Elevated transport of suspended sediments following years of extreme yield is uncommon in the Green Lake record and indicates a sediment-transport regime that is supply limited. For this watershed approximately 50 years of suspended sediment monitoring would be required to reduce the uncertainty of the yield estimate to 37% of its average value. A summer rainstorm in 1991 delivered more suspended sediment to the Green Lake Basin than any other event in the last 3000 years.

Keywords: Sediment yield; Rare event; Varves; Suspended sediment; Persistence; Uncertainty

1. Introduction

Specific sediment yield is defined as the mass of sediment delivered from a watershed, normalized by catchment area, and is conventionally reported as a yearly (Mg km^{-2} yr^{-1}) or daily (Mg km^{-2} day^{-1}) flux. This measure is not directly comparable to primary denudation rates due to sediment storage in hillslope and fluvial settings (e.g. Slaymaker, 1977; Pearce and Watson, 1983;Walling, 1983; Madej, 1987; Knox, 1990). Nevertheless, sediment yield obtained from diverse environments provides a means to assess how hydrology (Langbein and Schumm, 1958), lithology and morphometry (Walling and Webb, 1996; Church et al., 1999; Meybeck et al., 2003), glacier cover (Hallet et al., 1996), and land-use (Trimble, 1983; Blackburn et al., 1990) influence regional patterns of sediment production and transfers. Long records of sediment yield are useful in reconstructing hydro-climatic history (Desloges and Gilbert, 1994), geomorphic events (Major et al., 2000), and land-use change (Walling and Fang, 2003).

Conventional methods of estimating sediment yield require monitoring individual fractions of fluvial sediment load, namely, the dissolved, suspended, and bedload components. Suspended sediment transport is difficult to summarize since turbulent energy and complex patterns of sediment storage control suspended

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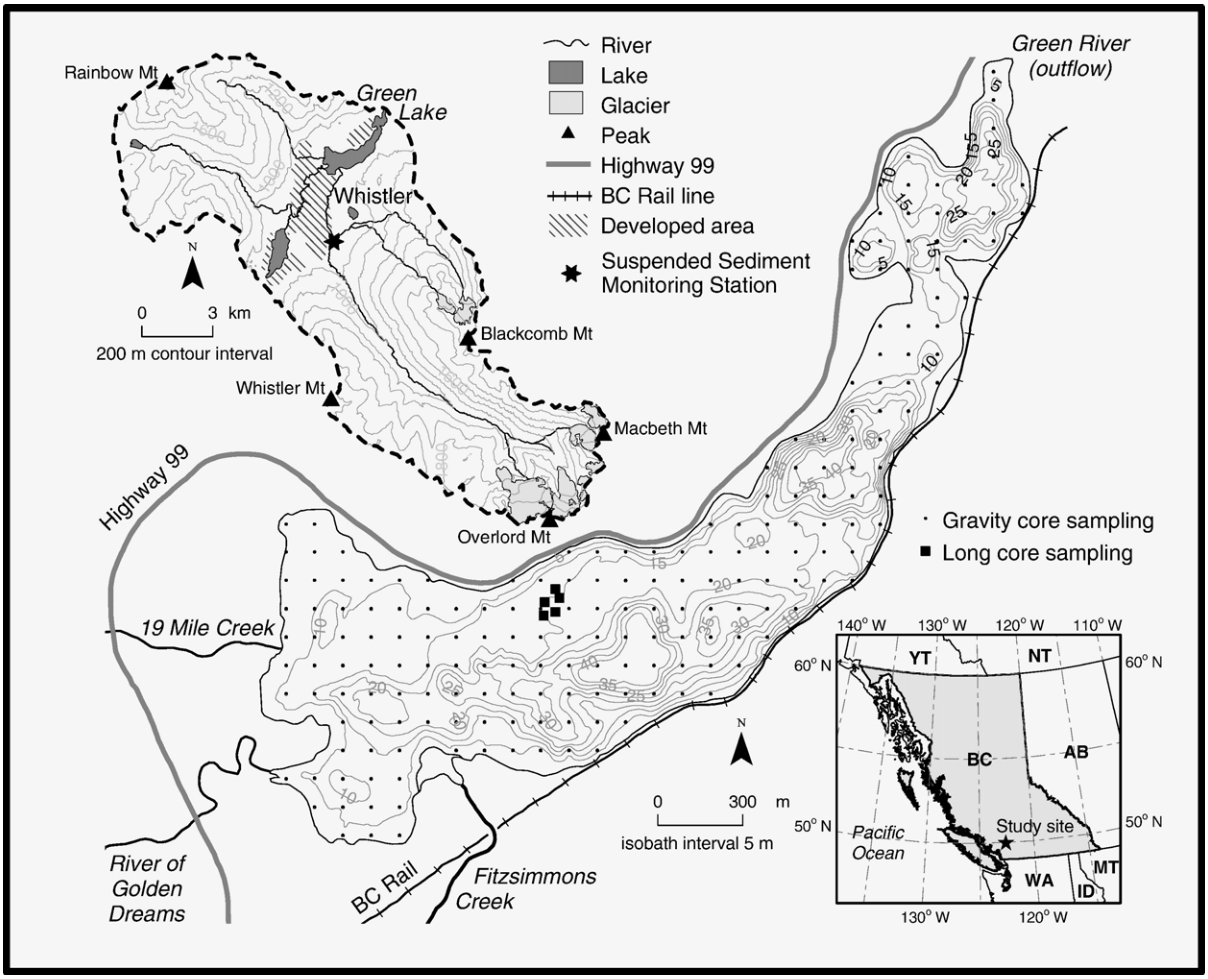

Fig. 1. Study area, Green Lake bathymetry, and core sampling locations.

sediment concentration (SSC). These complexities are noteworthy in small catchments where the majority of sediment transport occurs infrequently (Church et al., 1989; Meybeck et al., 2003).

Direct and indirect methods to measure SSC include collecting daily, weekly, or monthly SSC samples, or developing sediment rating curves that predict SSC from continuously recorded variables such as water discharge, turbidity, air temperature, or precipitation. However, direct measurement of SSC is expensive and sediment yields can be heavily biased if sampling strategies do not adequately sample high flows (e.g. Walling and Webb, 1982; Thomas, 1985). Turbidity measurements are often prone to errors due to fouling or perform poorly when a significant fraction of the suspended component is fine sand (Truhlar, 1978). Temporally-variable sediment availability can cause sediment rating curves to perform poorly on independent data sets (Bogen, 1980; Williams, 1989). Finally, bias imposed by record length affects all of these methods (Bunte and MacDonald, 1995) particularly in environments where the majority of suspended sediments are transported infrequently. This bias is severe for small, mountain watersheds of the Canadian Cordillera where significant sediment transporting events combine with infrequent sampling (Church et al., 1989).

An alternative method of estimating suspended sediment yield calculates the volume of clastic sediments delivered to lakes or reservoirs over time (Foster et al., 1988; Duck and McManus, 1994; Evans and Church, 2000). In ideal situations, lake sediments may be annually laminated (varved) and allow event to annual scale resolution and calculation of long-term trends in sediment yield (Lamoureux, 2000). Surprisingly, few studies compare fluvial and lake-based methods of estimating sediment yield. In studies by Dearing et al. (1982) and Al-Jibburi and McManus (1993), significant differences were reported between sediment yield

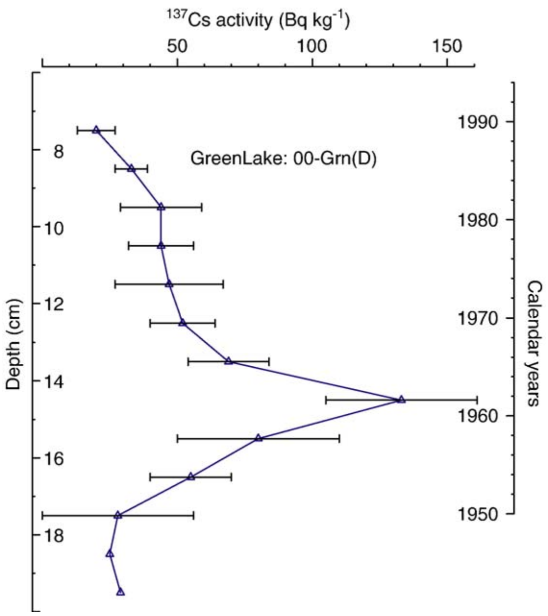

Fig. 2. Cesium activity of Green Lake gravity core 00-Grn(D) between 7.5 and 19.5 cm depth. Vertical error bars (dashed) denote the calendar age range (1 cm thick samples) for the sediment sample based on varve counting. Horizontal error bars reflect analytical uncertainty ($\pm 1\ \sigma$) in ^{137}Cs activity determination. The initial rise and peak levels of ^{137}Cs in the sediments coincide with the Northern Hemispheric air-fall record of cesium.

estimates derived from reservoir sedimentation and from fluvial monitoring. In both studies the monitoring was carried out for a single year so the origin of these differences remains uncertain. The objectives of this paper are: a) to establish lake-based yield records for historical (1931–2001) and long-term (3000 year) periods; b) to discuss the origins and significance of persistence in the sediment yield record; c) to evaluate bias in estimating mean sediment yield and return intervals for rare events caused by record length and; d) to compare fluvially based yields to sediment volume deposited in a proglacial lake over a 3-year period.

2. Study area and methods

Green Lake is an oligotrophic lake draining a medium-scale (178 km^2) watershed in the southern Coast Mountains of British Columbia, Canada (Fig. 1). The lake has a principal inflow (Fitzsimmons Creek) that delivers the majority of the water and sediment to the lake. Major sediment sources to the lake include contemporary ice cover (7% of catchment area), glacier forefields, and reworked Pleistocene valley fill. Maximum ice cover during the latter half of the ‘Little Ice Age’ (1700–1850) is estimated to have been 12%. The lake (1.99 km^2) is comprised of several individual basins and a wide, shallow sill in proximity to the contemporary delta of Fitzsimmons Creek (Fig. 1).

We recovered sediment cores from Green Lake from ice cover and from a raft during summer by percussion, gravity and vibra-coring techniques (Glew, 1989; Reasoner, 1993; Smith, 1998). The cores were split, photographed, and sampled for physical properties required for sediment yield determination (i.e. dry density, organic matter, and laminae thickness) using standard procedures. Laminated sediments were impregnated with low viscosity resin (Lamoureux, 1994, 2001) to prepare polished sediment slabs and thin sections required for identification and measurement of laminae. We also identified faint laminae from partially dried sediment cores (Gilbert, 1975). For the monitoring (1999–2001) and historical (1931–2001) periods we determined lake-based sediment yields from a dense (100 m) grid network of gravity cores ($n=136$) recovered from the lake (Fig. 1). The duration of the historical period is artificially imposed by the length of the gravity cores (10–50 cm), but it coincides with the beginning of climatic, land-use, and photographic records of the watershed.

There are three inflows to Green Lake but regular sediment monitoring was limited to Fitzsimmons Creek based on the following rationale: a) the Fitzsimmons watershed is the largest sub-basin draining into the lake; b) detailed field studies and air photo analysis indicate that this basin has the majority of visible sediment sources and contemporary glaciers (Fig. 1); c) Fitzsimmons Creek streamflow (Environment Canada streamflow station 08MG0026) has been continuously monitored by the Water Survey of Canada since 1995 and; d) analysis of suspended sediment concentration (SSC) for the other streams from 2000–2002 indicates that SSC is typically one to two orders of magnitude lower than in Fitzsimmons during concurrent sample collection. Nevertheless, we acknowledge that these unmonitored streams could represent significant sediment sources to the lake during pre-monitored extreme runoff events.

We collected 121 depth-integrated (DH-48) SSC samples from Fitzsimmons Creek over the 1999–2002 runoff seasons. Sampling frequency was approximately weekly during the snow melt and glacier runoff seasons and increased to 3–4 samples per day during high flows. Samples were collected along a straight, turbulent reach to maximize horizontal mixing. The sampling station was located along the left bank of the channel where the active channel was 5 m wide (Fig. 1). The cobble-to-boulder bed material near the sampling station maximized turbulence and no cross-channel variability in SSC was observed. Sediment concentration was determined gravimetrically, using 0.45 μm nominal pore size filters and oven drying (105 °C). Organic content (determined by ashing) was generally low (<1% by weight).

To estimate fluvial suspended sediment yield, we constructed a sediment rating curve for Fitzsimmons Creek. We used hourly stream flow to account for substantial fluctuations in SSC over periods less than a day. Not known to us until the completion of the study was the malfunction of water level equipment at the Fitzsimmons Creek gauging station that prevented recovery of complete discharge records for the study (Environment Canada-pers. comm). Given the large number of missing day, a synthetic discharge record was derived by regressing daily flow of Lillooet River (08MG005) against the Fitzsimmons record. The watersheds are in close proximity to one another, have comparable fractions of ice cover, but differ in area (99 vs. 2160 km^2). Correlation between daily flow records for the stations is strong (r^2=0.94).

3. Results

3.1. Lacustrine-based historical record (1931–2001)

Green Lake sediments are primarily laminated, inorganic silty clays to clayey silts. We recovered continuously laminated sediments from water depths proximal to Fitzsimmons Creek as shallow as 3 m and from sites ca. 10 m and deeper from more distal lake settings. Laminae consist of couplets with the lower silty lamina overlain by a thinner, clay-rich unit. Couplet thickness declines non-linearly from the Fitzsimmons delta and is locally thicker in deepwater areas of the major lake sub-basins (Fig. 1).

The couplets represent clastic varves based on the following lines of evidence: a) independently derived ages obtained using ^{137}Cs activity of the sediments (Fig. 2) and, for the longer record accelerator mass spectrometry (AMS) ^{14}C ages (Menounos, 2002); and b) new couplets predictably observed in cores taken in subsequent years. Varve thickness was defined by the sediments deposited between two clay laminae and cores were cross-dated using distinctive marker beds (e.g. Lamoureux, 2001). Varves deposited between 1931 and 1946 are inorganic, micro-laminated, and denser than those deposited from 1947 to 1990 which consist of simple couplets (Fig. 3). These simple couplets are commonly diffuse and less distinctive than varves deposited prior to 1946 and following 1991. Sediments deposited in the lake following 1991 are tan in color, slightly coarser, and frequently contain sub-annual laminae between the lowermost silts of the varve and the upper clay cap (Fig. 3).

We calculated sediment yield for the 1931–2001 period by determining the sediment flux for a given year for each sediment core, calculating the average annual flux for all coring sites, and then multiplying by lake area (Fig. 4). The clastic component for a given core site was determined by removing the organic matter fraction from the calculation. The modern sediments (younger

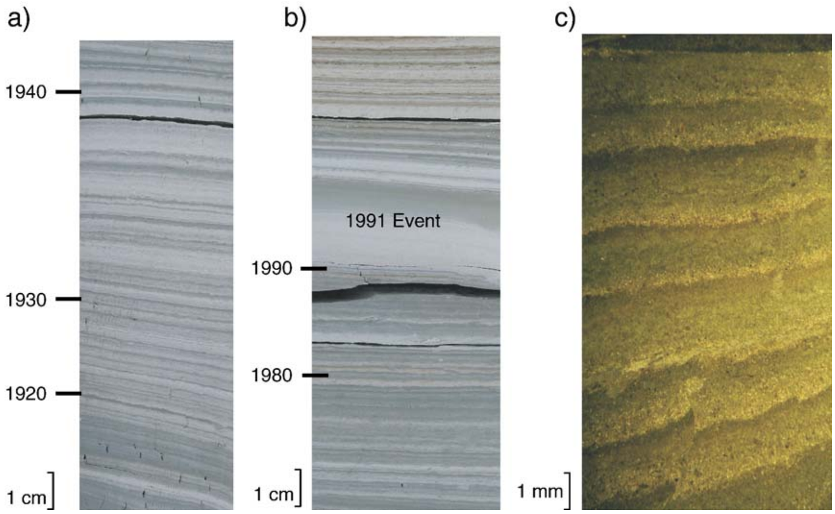

Fig. 3. Green Lake varves. a) Photographs of varves from 1900 to 1944; b) Late 20th century varves. Note the thickness of the 1991 event; c) microphotograph of thin section showing varves (simple couplets) from 138–134 cm depth (1456–1449AD).

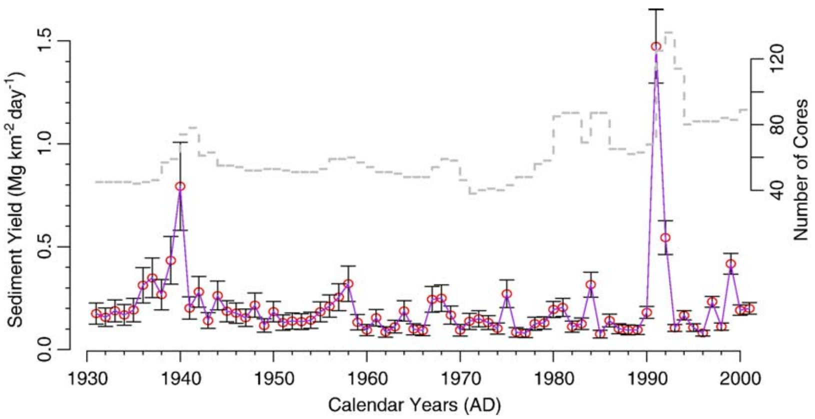

Fig. 4. Specific sediment yield for the 1931–1998 period. Error bars (95%) reflect combined analytical uncertainty introduced by laboratory techniques and trap efficiency (85%). Dashed line indicates number of contributing cores.

than 4000 years) of Green Lake contain insignificant (<1% by weight) biogenically produced carbonates or silica. The collection of the cores on a dense regular grid precluded the need to derive irregular contributing areas or corrections based on accounting for significant spatial variability of lake sedimentation (Evans and Church, 2000). The 2002 varve was excluded from the fluvial monitoring and lake-based yield comparison because of coring and laboratory-induced disturbance.

Adjacent cores situated in a similar depositional environment were used in order to construct sediment flux records at sites where a continuous chronology could not be established. This was necessary at some locations of exceptionally high sedimentation rates where the full length of record was not recovered, and at sites where post-depositional disturbances including slumping, physical reworking, and bioturbation confound the stratigraphic record.

Specific sediment yield through time is characterized by two patterns: a) inter-annual to decadal periods of elevated sediment yield (e.g. 1935–1946) and; b) years of exceptional yield (e.g. 1940 and 1991) (Fig. 4). We use the lag 1 autocorrelation coefficient (ρ_1) to quantify the magnitude of persistence in the sediment yield records. After correction of ρ_1 for low sample size (Wallis and O'Connell, 1972), the unbiased estimate of ρ_1 (0.30) remains significantly different from zero at $p=0.05$. Persistence in the yield time series is assumed to behave as a first-order Markov process where the current year's yield (Y_t) can be approximated by:

$$Y_t = \rho_1 \cdot Y_{t-1} + w_n \tag{1}$$

where (Y_{t-1}) is the previous year's suspended sediment yield, and w_n is a normal, random variance (Gilman et al., 1963; Mann and Lees, 1996). This persistence biases the standard error of the mean and requires a correction (Yevjevich, 1972). The unbiased sediment yield estimate for the 1931–1999 period is 0.21 $\pm$0.03 Mg km^{-2} day^{-1}.

3.2. Lacustrine-based long-term record: (last 3000 years)

The upper 5.5 m of recovered sediment from Green Lake consists of inorganic varves. A 3000-year record of sediment yield (Fig. 5) from the Green Lake basin was produced using a collection of longer sediment cores (1–5 percussion and vibracores) obtained from the sill location (Fig. 1). This site was chosen to record sedimentation by interflow and overflow events only and avoids biasing long-term rates by localized patterns of sedimentation (Lamoureux, 1999). We acknowledge, however, that this site will not record the underflow component of lake sedimentation which can represent an important lake sedimentation process (Gilbert, 1975; Lambert et al., 1976; Smith and Ashley, 1985).

Using standard methods to estimate the internal consistency of varve counting (Lamoureux, 2001), the mean error in varve age is $\pm$1.7%. Thickness measurements could not be completed on a 5 cm interval of bioturbated sediment, estimated from varve thickness above and below the interval to represent 40 years of sedimentation. We added 40 varves of random thickness to approximate the number and the thickness of missing varves. Two AMS ^{14}C radiocarbon ages (AA-38704: 1300$\pm$45 ^{14}C yr BP; and AA-38705: 1860$\pm$50 ^{14}C yr BP) were obtained from conifer needles from 241 and 342 cm, respectively. The calibrated age ranges (95%

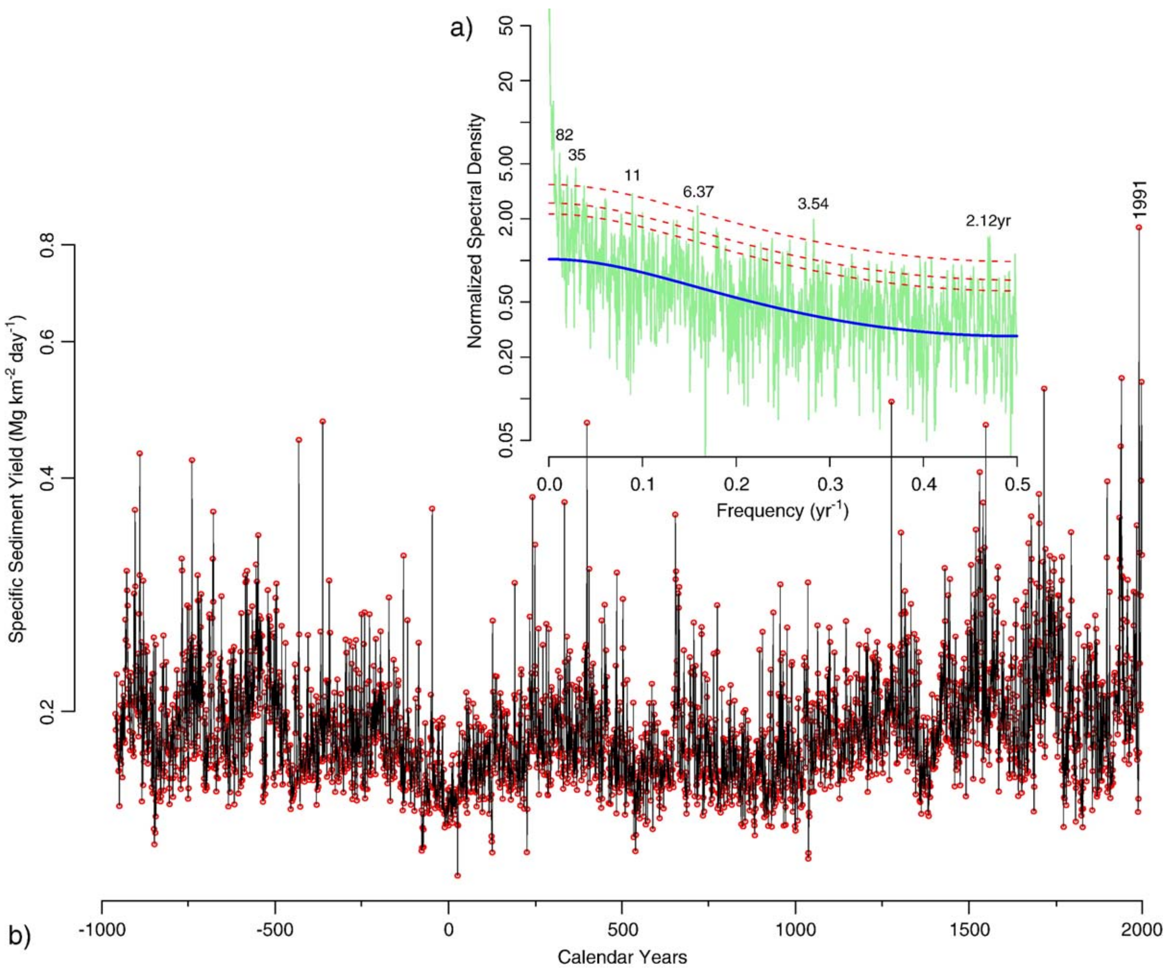

Fig. 5. Long-term specific sediment yield (Mg km^{-2} day^{-1}) for Green Lake and spectral power. (a) Normalized spectral density (zero mean; unit variance) of the Green Lake sediment yield time series (n=2960) with median (solid) and 90%, 95% and 99% confidence limits (dashed lines) based on a red noise null spectrum. (b) Specific sediment yield through time.

probability) for the radiocarbon samples (1300–1080 and 1920–1630 cal. yr BP) are close to the sediment age based on varve counting (1048–1012 and 1615–1555 cal. yr BP).

A varve chronology was produced by averaging varve thickness across the contributing cores for a given year (Fig. 5). Standardization was not required since varve thickness for a given year did not vary significantly between cores. Coring-induced disturbance of couplets, losses introduced following splitting cores into 1–2 m sections in the field, and incomplete dehydration of sediments prior to resin impregnation causes the number of contributing cores (approximately 1 core prior to 1000, 2 cores from 1000–1650; 4 cores from 1650–1800; 5 cores following 1800) to vary through time. Mean inter-series correlation among the individual records is 0.73.

We used bulk physical properties sampled at 1 cm resolution for one core, a depth-varve age model, and average varve thickness to derive sediment flux at the sill. The flux is multiplied by lake area to derive sediment yield. Varve thickness at the sill explains 80% of annual lake-wide sedimentation based on the network of the surface sediment cores. There is a slight bias for the chronology to under-predict years of extreme yield (e.g. 1940, 1984, 1991) and to record greater yield in years characterized by low sedimentation rates. The 2960-year record is dominated by century-scale variability (Fig. 5). The long-term estimate of specific suspended sediment yield to the lake basin is $0.19 \pm 7.6 \times 10^{-4}$ Mg km^{-2}day^{-1}. However, the regression model used to predict lake-wide sedimentation from the sill site biases the estimated standard error. A corrected standard error (SE_{total}) was determined using the standard error term from the regression model (SE_{model}) and the estimate determined from the sample size and variance (SE_{yield}):

$$SE_{total} = \sqrt{SE^2_{model} + SE^2_{yield}} \quad (2)$$

After autocorrelation is taken into account, the unbiased long-term estimate is 0.19±0.05 Mg km^{-2} day^{-1}.

3.3. Effects of sample size

We assess the importance of sample size in influencing standard errors by examining imprecision (±2SE of mean yield divided by the mean) as a function of record length (Fig. 6). The SE_{model} term was excluded from the analysis since it does not vary with record length. The importance of exceptional yields is revealed as imprecision changes from 50% to 70% with the inclusion of the 1991 varve (Fig. 6). Uncertainty does not decline substantially (<50%) for an additional 20 years. A record length of 185 and 487 years is required to reduce uncertainty to ±10% and ±5%, respectively (Fig. 6).

We examined autocorrelation bias by generating bootstrapped, confidence limits (95%, 99%, 99.99%) for the Green Lake sediment yield data (Fig. 6). Equal length, synthetic records (10,000) were generated from the original time series by replacement sampling. This method produced an ensemble of records with similar distribution moments as the original time series but lacking red noise (i.e. series that do not conform to Eq. (1)). Greater uncertainty is observed in the original record of yield compared to these records lacking autocorrelation (Fig. 6). This memory continues to have measurable effects (>10%) up to 150 years (Fig. 6).

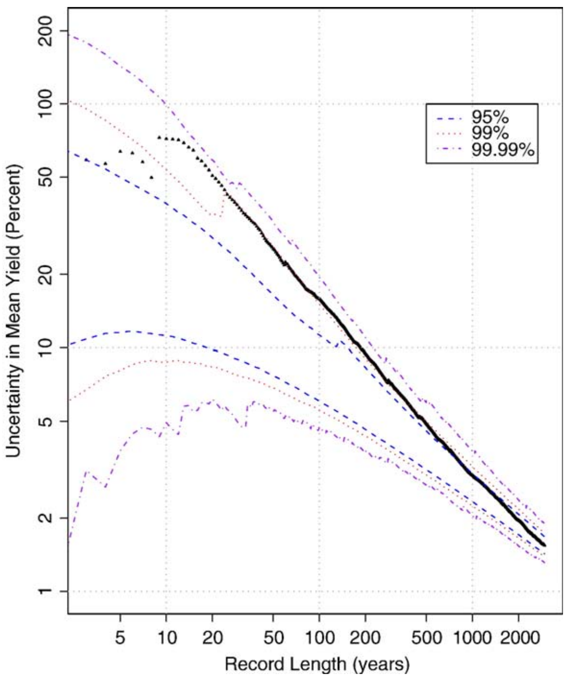

Fig. 6. Record length (years) and percent uncertainty in mean sediment yield. Triangles denote original time series. Confidence limits reflect 95%, 99%, and 99.99% quantiles (n=10,000) of series lacking autocorrelation.

3.4. Origin of persistence

We decomposed the Green Lake sediment yield record spectrally to evaluate whether observed persistence was periodic. The record was first transformed to a normal distribution using a Box–Cox transformation (λ=−2.12). The normalization is not required to determine periodicity in the series but is necessary for significance level testing (Hegge and Masselink, 1996; Mann and Lees, 1996). Using multi-taper spectral methods with a red-noise model (i.e. Eq. (1)) as the null spectrum (Gilman et al., 1963), significant ($p<0.01$) power is observed at century (82 yr), multi-decadal (52, 35 yr), decadal (11, 6 yr), and inter-annual (3.5, 2.1 yr) periodicities (Fig. 5).

To evaluate non-periodic persistence in the yield series, we employed a form of composite (epoch) analysis on the long-term sediment yield time series. Non-periodic persistence may arise from evacuation of stored sediment in fluvial or hillslope settings following years of flooding (Simon, 1999). We selected rare events (90, 98, and 99 quantiles) from the record, and averaged yield for the preceding decade, for the quantile in question, and the subsequent 50 years. These intervals were selected so that our results were comparable to previous work (Lamoureux, 2001).

A lack of notable persistence following years of extreme yield is observed in the Green Lake record (Fig. 7). Cumulative departures of yield following rare events indicate marginally increased yields for the first 5 years (positive slope), a period (yr 10–30) characterized by a lack of persistence (slope close to zero), followed by subsequent decline. There is a weak association between high yields in the years prior to rare events (Fig. 7). Higher persistence is observed for events with lower return intervals (10–20 yr; 10-yr patterns are not shown). Micro-stratigraphic analysis of the moderately thick varves (10–50 yr. events) indicates that most consist of either simple couplets or are micro-laminated. In contrast, the thickest varves (100 yr. events) comprise a

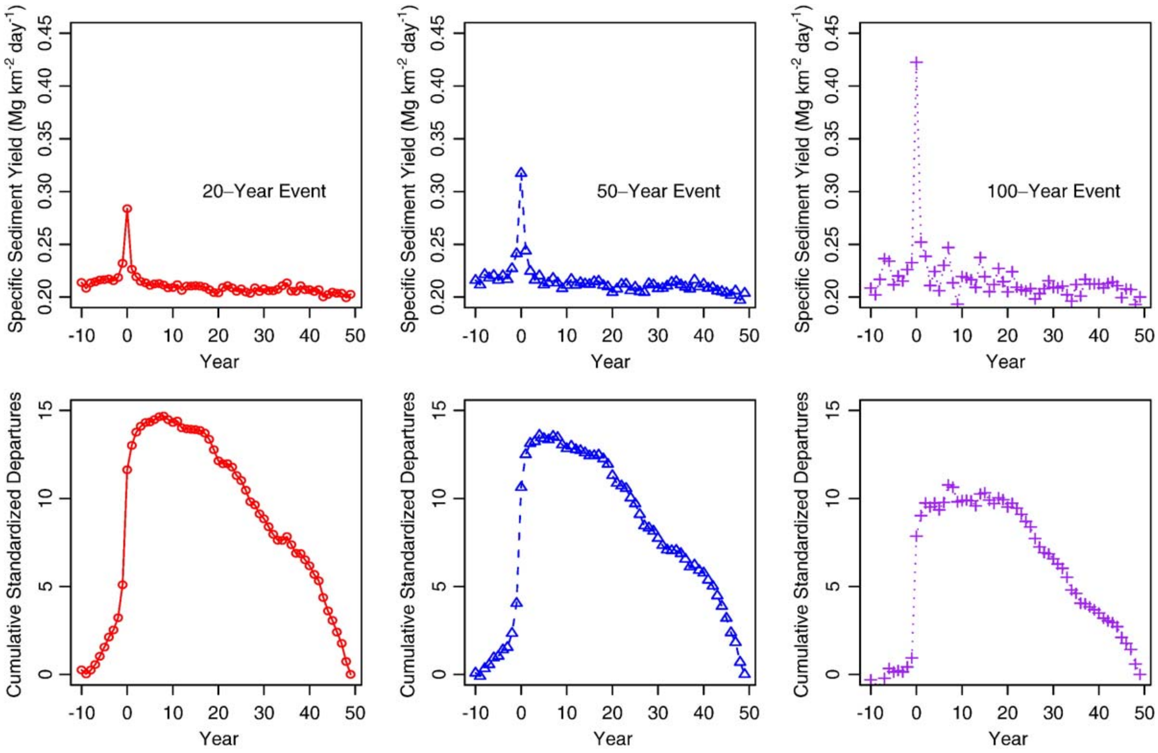

Fig. 7. Observed persistence in sediment yield following rare events. Upper panel illustrates averaged yields for the preceding decade and 50 years following 20, 50 and 100-year return intervals. Lower panel shows cumulative departure trends for a given return-interval.

lowermost silty lamina that is abruptly overlain by graded silts capped by clay.

3.5. Return interval estimation of the 1991 event

The Green Lake sediment yield record presents an opportunity to assess the bias of return interval estimates from short records. Approaches using short monitoring records are parametric in nature where the available record is assumed to originate from an underlying distribution. Typically these distributions are positively skewed (e.g. Lognormal, Gumbel, Generalized Extreme Value). Parameters are estimated after fitting the sample to an underlying distribution to determine return intervals. To evaluate the potential for short-record bias (Klemeš, 2000), we calculated the return interval for the 1991 event in records of varying length. We first compared the 3000-year record to skewed distributions commonly used to estimate sample quantiles. The long-term yield data set is best represented as a generalized extreme value distribution (GEV):

$$p(x) = 1-e^{\left[-\left(1+\frac{s\cdot(x-a)}{b}\right)\right]^{\frac{1}{s}}} \tag{3}$$

where $p(x)$ is the probability of the observation (x) given the location (a), scale (b) and, shape (s) parameters. Maximum likelihood methods were used to estimate model type and parameter values and were highly significant ($p<1\times10^{-5}$) irrespective of sample length. Return Intervals (RI) of the 1991 event $\left(\frac{1}{1-p(x)}\right)$ were developed by estimating a GEV model for varying lengths of record from 50 to 2960 years (Fig. 8).

The exceptional nature of the 1991 event is not apparent in the first 180 years of record, but by 200 years, the RI is five times the length of record and steadily increases to a maximum RI of 52,000 years (Fig. 8). The RI for the 1991 event is not realistic since Green Lake was under Pleistocene ice 12,000 years ago. The second largest yield (0.53 Mg km^{-2} day^{-1}) has a RI of 2850 years. The shape parameter influences the extreme nature of the 1991 event most apparently. The shape value decreased from 0.4–0.3 for a record length of several hundred years to 0.2–0.15 including the entire data set. Both the location and scale values undergo monotonic decreases to final values of 0.18 and 0.02, respectively. These results show the importance of sample size on return interval estimation.

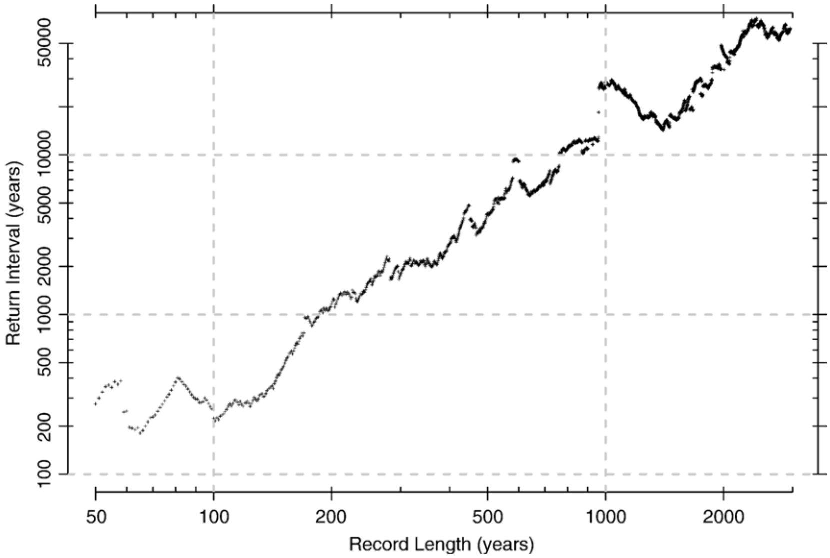

Fig. 8. Estimated return intervals for the 1991 event.

3.6. Fluvially based monitoring record: (1999–2001)

Based on the monitoring program, observed suspended sediment transport occurs during three hydrologic seasons: 1) snowmelt runoff from early May to early July; 2) glacier runoff during late July to mid September and; 3) infrequent precipitation events of late summer and autumn. Sediment concentration varies from >5 mg l^{-1} during low flows of late autumn, winter, and early spring to <1000 mg l^{-1} during high flow events (>10 m^3 s^{-1}). High flows are common during the nival runoff season, and less frequent during late summer and autumn (Fig. 9). Highest measured SSC (4450 mg l^{-1}) occurred during a rainfall-all-driven bankfull discharge event during November 2001 (Fig. 9).

For those storms in which multiple samples were collected, the SSC-discharge (Q) relations exhibit clockwise hysteresis, common to environments where SSC is influenced by variable sediment supply (Williams, 1989). We log-transformed the SSC-Q data, but despite the transformation, significant scatter remains and decreases with increasing Q (Fig. 10). The decrease could arise from fewer SSC measurements at higher Q but may also result from seasonally-dependent sediment transport common to proglacial streams of the southern Coast Mountains (Menounos, 2002; Richards and Moore, 2002). Because Fitzsimmons Creek basin is lightly

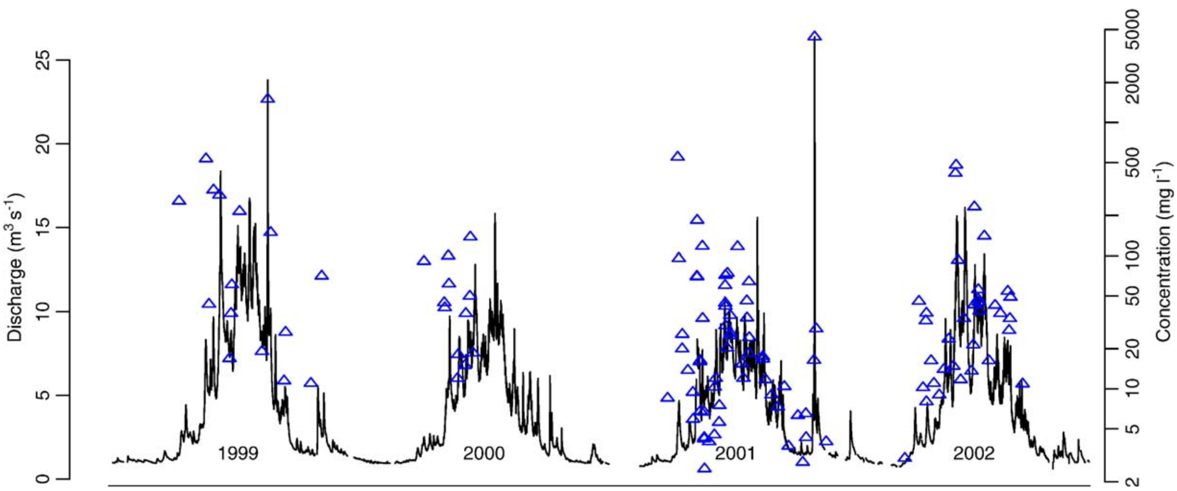

Fig. 9. Fitzsimmons Creek streamflow record and suspended sediment concentration (open triangles) data for the 1999–2002 hydrologic seasons.

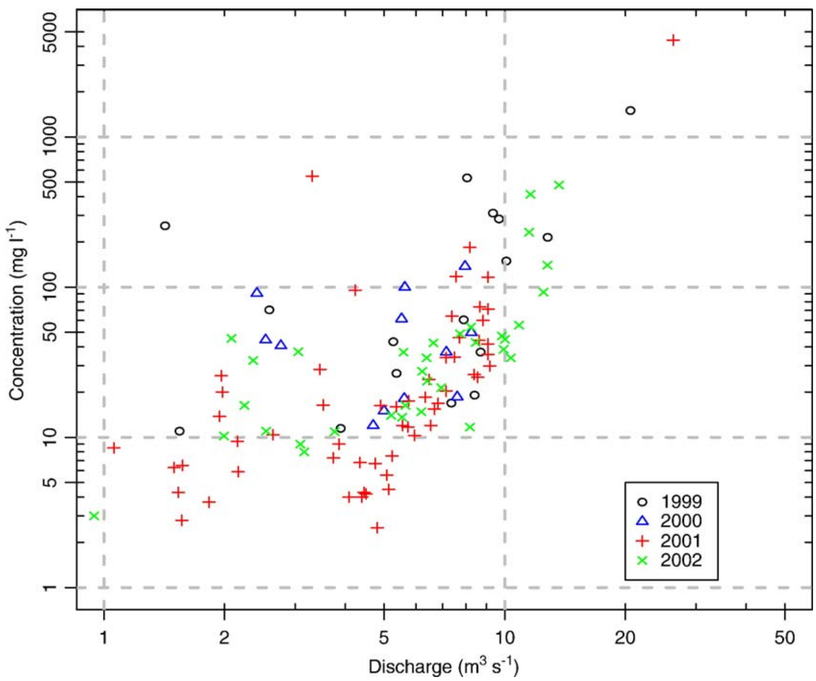

Fig. 10. Suspended sediment concentration–discharge relation.

glacierized (7%), SSC increases during the glacial runoff season which occurs on the declining limb of the annual, snowmelt-dominated hydrograph.

Two sediment rating curves (weighted and threshold) were developed by examining a number of predictor variables for lnSSC including hourly discharge (Q), change in discharge (ΔQ), precipitation, air temperature, and time trend (t). ΔQ was calculated by differencing the current flow (lag$_{t=0}$) with discharge in the past and weighs discharge preceding peak runoff more heavily than on the declining limb where sediment exhaustion effects are common (e.g. Richards, 1984; Thompson et al., 1987). We optimized ΔQ by determining the highest correlation between ΔQ and lnSSC between 1 and 500 h which was at 94 h (3.9 days). There is a declining trend in the SSC data over the monitoring period so a trend component was also included.

Weighted least squares analysis was used in the first sediment rating curve. Q was used as the weighting function because variance in SSC decreases with increasing Q and the importance of high flows in influencing total yield from mountain watersheds (e.g. Church et al., 1989; Pitlick, 1993; Costa and O'Connor, 1995). Unlike many studies examining proglacial suspended sediment yields (e.g Fenn, 1989; Bogen, 1996), significant inter-annual variations in the Q-SSC relation was not observed (Fig. 10). It remains uncertain whether similar ratings are due to low sample size ($n=121$) or seasonally stable sediment transfers from year to year. Highly variable, inter-annual sediment rating curves are commonly observed in catchments with higher glacier cover than that of this study (Collins, 1996; Richards and Moore, 2002). A 3-parameter model incorporating Q, ΔQ_{94}, and trend (t) explains 74% of the lnSSC variance observed during the monitoring period (Table 1). Model adequacy was evaluated by examining the distribution and autocorrelation of residuals. Most outliers occurred at low flow conditions (1 m^3 s^{-1}) during late autumn, early winter or early spring with SSC below 5 mg l^{-1}. The moderate proportion of explained variance, in addition to autocorrelated residuals (significant up to lag 4), highlights the model inadequacy.

Inspection of the lnSSC-ln$Q$ relation indicates a discharge (5 m^3 s^{-1}) above which scatter decreases significantly (Fig. 10). We developed a second sediment rating curve (threshold) as an alternative to the model incorporating the entire data set. Residuals from the threshold model exhibit less autocorrelation (only the first lag is significantly different from zero), and the model has a lower standard error (Table 1). We did not observe any improvement in predicting SSC by developing seasonally dependent rating curves for our data and suspect that this is a result of low sample size. For example, SSC during the glacier runoff season is higher than during comparable flows of late spring or early autumn (Fig. 9).

Table 1
Comparison of fluvial and lake-based sediment yields for the 1999–2002 period

Year	1999	2000	2001	2002	Average
Fluvially based yield (3 parameter)[a]	0.52	0.12	0.20	0.13	0.24±0.09[b]
Fluvially based yield (3-parameter threshold)[c, d]	0.40	0.09	0.11	0.10	0.17±0.07
Fluvially based yield (average)	0.46	0.11	0.15	0.12	0.21±0.08
Lake-based yield	0.42	0.19	0.20	–	0.27±0.07

Yield estimates corrected for negative bias (1.87 and 1.27, respectively) introduced by log transformation by $\sum_{i=1}^{i=n}\exp(e_i)$ where e_i is the ith residual from the regression (Finney, 1941). The estimates have been based on a contributing basin area of 178 km^2 to allow comparison to the lake-based estimates.

[a] [$R^2_{\mathrm{adj}}=0.74$; F-statistic: 107.2 on 3 and 114 df, p-value: $<2.2\times10^{-16}$, Residual Standard Error=7.64 mg l^{-1}. All parameters are significant ($p<0.01$)].

[b] Standard error of the mean $\left(\frac{\sigma}{\sqrt{n}}\right)$.

[c] [$R^2_{\mathrm{adj}}=0.71$; F-statistic: 65.3 on 3 and 76 df, p-value: $<2.2\times10^{-16}$, Residual Standard Error=1.99 mg l^{-1}. All parameters are significant ($p<0.01$)].

[d] Assuming zero sediment concentration for discharge <5 m^3 s^{-1}.

The regression models (weighted and threshold) were used to derive hourly SSC for the 1999–2002 period. These measurements were combined with the Fitzsimmons Creek discharge record and corrected for negative bias introduced by the log transformation (Finney, 1941) to derive yield estimates for the 1999–2002 period (Table 1). We use the average of these two statistical models (0.21±0.08 Mg km^{-2} day^{-1}) as the best estimate of the fluvially based sediment yield for the basin.

4. Discussion

4.1. Comparison of fluvial and lake-based yield estimates

Suspended sediment yields for the Green Lake Basin estimated through fluvial monitoring (0.21±0.08 Mg km^{-2} day^{-1}) and lake-based methods (ca. 0.27 ±0.07 Mg km^{-2} day^{-1}) are similar over the period 1999–2001 (Table 1). Variations in yearly suspended sediment yield are caused by variable runoff rather than significant changes in the relation between Q and SSC (Figs. 9 and 10). Reasonable agreement is also observed for the period of overlap between the historical (0.21 ±0.03 Mg km^{-2} day^{-1}) and long-term (0.19±0.05 Mg km^{-2} day^{-1}) estimates. This concordance suggests that a lake-based approach is an appropriate method to estimate long-term suspended sediment yields for the Green Lake watershed. The major advantage afforded by the lake sediment record is the considerably longer record it provides (Lamoureux, 2000). This technique will have greatest utility in environments where suspended sediments are transported during extreme runoff events that may be missed by monitoring programs.

Although the two methods of estimating sediment yield are comparable, a two-fold increase in the precision of the estimate is observed for the lake sediment yield estimate. Nevertheless, years of extreme yield continue to elevate standard errors. For example, the removal of the two largest yield years from the record (1984, 1991) decreases the 1931–1999 yield estimate by 9% but reduces the standard error term by 36%. The high inter-annual variability observed in the Green Lake record appears to be a common feature in long-term sediment delivery records from the southern Coast Mountains (Desloges and Gilbert, 1994).

We recognize that the close agreement between the sediment monitoring and lake-based approach may be a fortuitous result. The short period of overlap did not contain extreme events which could be missed by the monitoring program but recorded in the lake sediments. Similarly, our fluvially based sediment yield estimates are subject to errors and limitations common to SSC data sets of low sample size (Thomas, 1985). Low sample size prevents a detailed analysis of the seasonal differences in suspended sediment transfers for Fitzsimmons Creek and consequently, the development of improved sediment rating curves.

4.2. Interpretation of 20th century yield patterns

Elevated yields during the 1935–1945 period are attributed to an increase in sediment availability following rapid ice retreat from 'Little Ice Age' positions (Slaymaker et al., 2003). Surface area losses of Overlord and Fitzsimmons glaciers between 1928–1931 and 1987 are comparable in magnitude (15% of total area) to changes in glacier area between 1700 and 1928/1929. Most rapid 20th century retreat (ca. 30 m yr^{-1}) of Fitzsimmons and Overlord termini occurred during the 1929–1949 period (Menounos, 2002). Varves deposited between 1935 and 1945 are commonly micro-laminated; underlying coarsegrained silts are overlain by up to 10, sub-millimeter laminae (Fig. 3). This stratigraphy is consistent with sediments delivered during multiple rather than single inflow events to the lake (e.g. Gilbert, 1975; Desloges and Gilbert, 1994).

Differences in the physical properties of sediments deposited after 1991 reflect a change in sediment sources to the lake basin (Fig. 3). A late summer rainstorm in 1991 produced the second largest flood on Lillooet

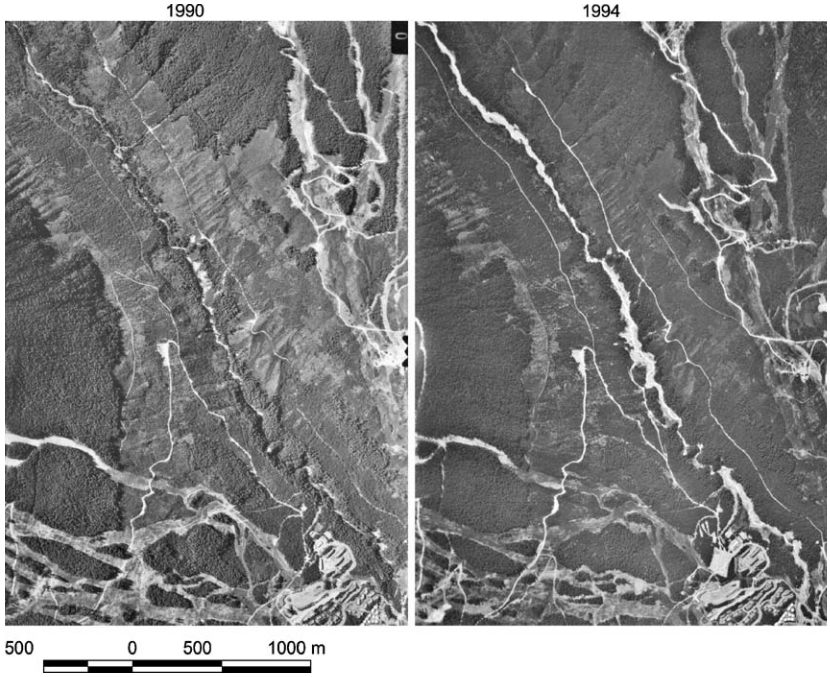

Fig. 11. Fitzsimmons Creek prior to and following the 1991 flood. Blackcomb Mountain base lodge is visible in the lower right-hand side of the photos.

River. Estimated return intervals for the event range from 20 years (yearly one-day rainfall) to 100 years (summer only) (Ward and Skermer, 1992). In the Green Lake watershed, the event triggered a deep-seated landslide that temporarily dammed Fitzsimmons Creek, and caused aggradation and, later, scour in excess of 5 m (Ward and Skermer, 1992). Channel surveys (Ward and Skermer, 1992) and air photos indicate substantial increases in sediment storage in the fluvial network following the event (Fig. 11). Gullies and landslide scars produced during the 1991 event remain unvegetated and have become important sediment sources to Fitzsimmons Creek. These changes, in addition to gravel extraction in Fitzsimmons Creek to alleviate flooding risk, have enhanced the delivery of non-glacial sediments to the lake basin.

The period of most rapid land-use development in the Green Lake watershed (1950–1980) does not coincide with higher sediment yield (Fig. 4). Most land use occurred on areas of low relief that are decoupled from the fluvial network. Consequently, any evidence of land-use effects on the historical patterns of sediment yield is

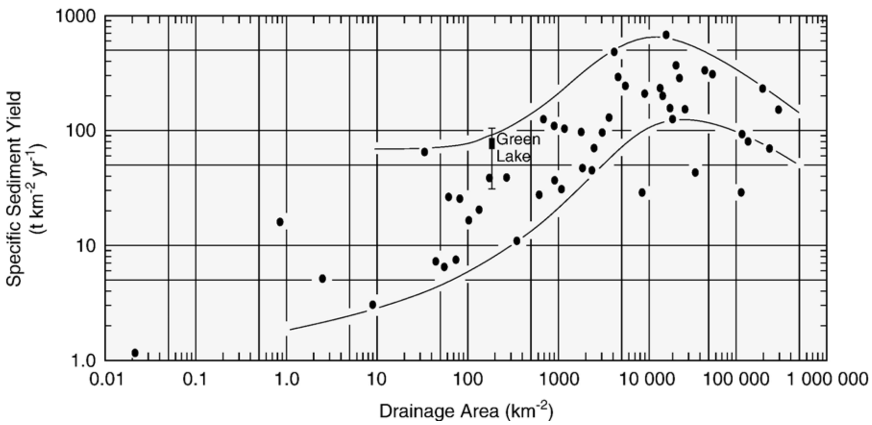

Fig. 12. Comparison of Green Lake sediment yield (open square with ±2 standard error bars) with estimates based on fluvial sediment monitoring for British Columbia. Fluvial data from Church and Slaymaker (1989).

masked by rapid sedimentation caused by glacier recession in early 20th century and changes in sediment availability after 1991.

4.3. Comparison to the regional pattern of sediment yield

Sediment yield for the Green Lake watershed is consistent with the regional pattern observed in British Columbia (Fig. 12). Specific sediment yield increases up to a basin scale of 3×10^4 km^2 with subsequent decline thereafter. This pattern is best explained by the incremental contribution of reworked Quaternary sediments to sediments produced by primary denudation in intermediate watersheds (Slaymaker, 1987; Church and Slaymaker, 1989; Church et al., 1989).

Estimated suspended sediment yields for Green Lake are higher than lake-based values for non-glacierized watersheds in the Coast Mountains (Schiefer et al., 2001). Glaciers represent important sites of primary sediment production and their influence on elevating suspended sediment yields in the Coast Mountains (Desloges and Gilbert, 1994, 1998) and elsewhere (e.g. Harbor and Warburton, 1993; Hallet et al., 1996) is well known. The close relation between maximum rates of glacier recession and increased lake sedimentation in the Green Lake Basin is consistent with findings from nearby glacierized watersheds (Menounos, 2002) and from the Canadian Rockies (Leonard, 1997). In contrast, a recent study examining the relation between sediment yield and glacier extent in coastal Alaska observed lowest sediment yields during years of rapid ice retreat (Loso et al., 2004). Geomorphic factors responsible for these differences may include differences in the efficiency of fine sediment production by glacier abrasion, sediment routing of fines following ice retreat, or reworking of deposits in glacier forefield locations. Additional studies that compare inter-annual to decadal changes in ice cover to downvalley lake sedimentation over a common time interval may clarify the relation between glacier fluctuations and suspended sediment yield.

4.4. Importance of record length, extreme events, and persistence

Increased precision and an evaluation of the representativeness of contemporary yields are two benefits of the lake-based methods adopted in this study. Variable sediment transport in small mountain watersheds or subtle changes in delivery caused by land use or climatic change require precise yield estimates. For the Green Lake watershed, the time required to reduce the percent uncertainty in mean yield to 37% (e-folding time) is approximately 50 years. This time exceeds the length of almost all sediment monitoring programs and highlights the major limitation of fluvial sediment monitoring, namely the brevity of the record.

Our findings reiterate the geomorphic importance of rare meteorological events in small watersheds of the Canadian Cordillera (Church et al., 1989). Despite a record length of nearly 3000 years, the 1991 event remains the event of record (Fig. 5). The 1991 event also influenced bed load transport rates for Fitzsimmons Creek (Pelpola and Hickin, 2003) and was responsible for major channel change on rivers near Whistler (Menounos, 2002). Decadally reconstructed bed load transport rates for Fitzsimmons Creek indicate a pronounced increase in bedload transport in the past decade (Pelpola and Hickin, 2003). These data also confirm the high-energy environment of this small mountain watershed and the importance of the bedload fraction of total sediment yield. Though the assumption that bedload represents 50% or less of the total clastic load has recently been questioned for a glacierized watershed (Loso et al., 2004), Fitzsimmons Creek transports comparable volumes of bedload ($1.6\pm0.28\times10^4$ Mg) and suspended sediments ($1.93\pm0.05\times10^4$ Mg) annually. Nevertheless, the variable nature of sediment transport in mountain environments requires empirical measurements of the suspended, dissolved, and bedload fractions of clastic sediment yield to obtain reliable, long-term estimates of total sediment yield.

Estimating rare events based on short monitoring records requires an assumption that events are independent and drawn from an underlying distribution in which sample parameters of the distribution approximate those of the population. Clearly, this assumption is not valid for the Green Lake record. Our findings reiterate the dangers of estimating rare events from short records (Klemeš, 2000). They also concur with a recent study that highlights the limitations of design-storm estimation from short, sparsely distributed hydrologic records in western Canada (Jakob and Jordan, 2001). The disadvantages in using geomorphic methods to estimate rare events are quickly superseded by the benefits of a longer record.

4.5. Comparison of persistence to previous studies

Greater memory ($\rho_1=0.37$) is observed in the long-term sediment yield data than in the historical record ($\rho_1=0.30$). This persistence may originate from periodicities in environmental factors influencing sediment yield, such as temperature and precipitation. It may also reflect geomorphic factors such as glacier response times or perhaps adjustments of the fluvial network following sediments introduced during glacier retreat, landsliding, or other processes (e.g. Gilbert, 1917; Simon, 1999). Fluvial sediment storage and exhaustion effects have been suggested to represent an important source of memory in other long-term records of sediment yield (Lamoureux, 2001).

Lamoureux (2002) examined short-term persistence of yields following rare events for a small watershed in the Canadian Arctic. For that environment, yields were elevated following rare (>50 yr RI) events but consistent behavior following smaller events was not observed. An opposite pattern is revealed in the Green Lake record. Greater persistence following small-to-moderate events (10–20 year events) may be expected if yield is controlled by climatic patterns with similar periodicities. Decadal-scale variability is commonly observed in long-term proxy records from the North Pacific Region (Minobe, 1997; Gedalof et al., 2002). The micro-laminated nature of varves of moderate thickness and the relation between varve thickness and air temperature for Green Lake supports this hypothesis (Menounos, 2002).

Variable patterns of sediment storage may explain the observed differences in persistence in the Green and Nicolay Lake records (Lamoureux, 2002). Nicolay Lake drains extensive areas of glaciomarine and glaciolacustrine sediments, the major source of suspended sediments for the lake basin. These fine-grained sediments are readily detached from upland, snow-free areas and deposited in channel settings. The source and sediment storage pattern of these fine-grained deposits contrasts with observations made for the Green Lake watershed. Prior to 1991, sources of suspended sediments were limited to glacier forefields, contemporary glaciers, and infrequent debris flows in first and second-order channels.

5. Conclusions

Comparable estimates of suspended sediment yield were obtained by fluvial sediment monitoring and using lake-based methods for a mountain watershed in the southern Coast Mountains of British Columbia. The advantage afforded by the lake-based approach has been to improve the reliability of the average yield estimate by increasing record length. Reconstruction of sediment yield using lake sediments has greatest utility in small mountain watersheds where the majority of suspended sediment is transported infrequently.

Persistence in the long-term record is dominated by low frequency, periodic behavior. The persistence has a negative effect on estimating the mean sediment yield by inflating standard errors. Persistently, high yields following extreme events are uncommon in the Green Lake and taken to reflect a sediment-transport regime that is supply limited.

One of the most important findings of this study has been to elucidate the rare nature of the 1991 event. Despite the 3000-year perspective afforded by the lake sediment record, the rarity of the event remains. Based on recovery of short sediment cores from other nearby lakes, the extreme nature of the event was not limited to the Green Lake basin (Menounos, 2002). Analysis of longer, varved sediment records from these environments is in progress to determine the regional significance of this event in southwestern British Columbia.

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References

Al-Jibburi, H., McManus, J., 1993. Estimation of sediment yields in the Cameron Reservoir catchment, Fife, Scotland, using two different approaches. In: McManus, J., Duck, R.W. (Eds.), Geomorphology and Sedimentology of Lakes and Reservoirs. John Wiley & Sons, Chichester, pp. 93–104.

Blackburn, W.H., Knight, R.W., Wood, J.C., Pearson, H.A., 1990. Stormflow and sediment loss from intensively managed watersheds in east Texas. Water Resources Bulletin 26, 465–477.

Bogen, J., 1980. The hysteresis effect of sediment transport systems. Norwegian Journal of Geography 34, 45–54.

Bogen, J., 1996. Erosion rates and sediment yield of glaciers. Annals of Glaciology 22, 48–52.

Bunte, K., MacDonald, L.H., 1995. Detecting change in sediment loads: where and how is it possible? IAHS Publication 226, 253–261.

Church, M., Slaymaker, O., 1989. Disequilibrium of Holocene sediment yield in glaciated British Columbia. Nature 337, 452–454.

Church, M., Kellerhals, R., Day, T.J., 1989. Regional clastic sediment yield in British Columbia. Canadian Journal of Earth Sciences 26, 31–45.

Church, M., Ham, D., Hassan, M., Slaymaker, O., 1999. Fluvial clastic sediment yields in Canada: scaled analysis. Canadian Journal of Earth Sciences 36, 1267–1280.

Collins, D.N., 1996. A conceptually based model of the interaction between flowing meltwater and subglacial sediment. Annals of Glaciology 22, 224–232.

Costa, J.E., O'Connor, J.E., 1995. Geomorphically effective floods. In: Costa, J., Miller, A.J., Potter, K.W., Wilcock, P.R. (Eds.), Natural and Anthropogenic Influences in Fluvial Geomorphology. American Geophysical Union Monograph, vol. 89, pp. 45–56.

Dearing, J.A., Foster, I.D.L., Simpson, A.D., 1982. Timescales of denudation: the lake-drainage basin approach. IAHS Publication 137, 351–360.

Desloges, J.R., Gilbert, R., 1994. Sediment source and hydroclimatic inferences from glacial lake sediments: the postglacial sedimentary record of Lillooet Lake, British Columbia. Journal of Hydrology 159, 375–393.

Desloges, J.R., Gilbert, R., 1998. Sedimentation in Chilko Lake: a record of the geomorphic environment of the eastern Coast Mountains of British Columbia, Canada. Geomorphology 25, 75–91.

Duck, R.W., McManus, J., 1994. A long-term estimate of bedload and suspended sediment yield derived from reservoir deposits. Journal of Hydrology 159, 365–373.

Evans, M., Church, M., 2000. A method for error analysis of sediment yields derived from estimates of lacustrine sediment accumulation. Earth Surface Processes and Landforms 25, 1257–1267.

Fenn, C.R., 1989. Quantifying the errors in transferring suspended sediment rating equations across ablation seasons. Annals of Glaciology 13, 64–68.

Finney, D.J., 1941. On the distribution of a variable whose logarithm is normally distributed. Journal of the Royal Statistical Society London. Series B 7, 155–161.

Foster, I.D.L., Dearing, J.A., Grew, R., 1988. Lake-catchments: an evaluation of their contribution to studies of sediment yield and delivery processes. IAHS Publication 174, 413–424.

Gedalof, Z., Mantua, N.J., Peterson, D.L., 2002. A multi-century perspective of variability in the Pacific Decadal Oscillation: new insights from tree rings and coral. Geophysical Research Letters 29, 2204–2207.

Gilbert, G.K., 1917. Hydraulic-mining debris in the Sierra Nevada. USGS Professional Paper, vol. 105. USGS (United States Geological Survey), Washington, D.C.

Gilbert, R., 1975. Sedimentation in Lillooet Lake, British Columbia. Canadian Journal of Earth Sciences 12, 1697–1711.

Gilman, D.L., Fuglister, F.J., Mitchell, J.M., 1963. On the power spectrum of "red noise". Journal of the Atmospheric Sciences 20, 182–184.

Glew, J.R., 1989. A new trigger mechanism for sediment samplers. Journal of Paleolimnology 2, 241–243.

Hallet, B., Hunter, L., Bogen, J., 1996. Rates of erosion and sediment evacuation by glaciers: a review of field data and their implications. Global and Planetary Change 12, 213–235.

Harbor, J.M., Warburton, J., 1993. Relative rates of glacial and nonglacial erosion in alpine environments. Arctic and Alpine Research 25, 1–7.

Hegge, B.J., Masselink, G., 1996. Spectral analysis of geomorphic time series: auto-spectrum. Earth Surface Processes and Landforms 21, 1021–1040.

Jakob, M., Jordan, P., 2001. Design flood estimates in mountain streams — the need for a geomorphic approach. Canadian Journal of Civil Engineering 28, 425–439.

Klemeš, V., 2000. Tall tales about tails of hydrological distributions. Journal of Hydrologic Engineering 7, 227–231.

Knox, J.C., 1990. Long and short term episodic storage and removal of sediments. IAHS Publication 184, 157–164.

Lambert, A., Kelts, K.R., Marshall, N.F., 1976. Measurements of density underflows from Walensee, Switzerland. Sedimentology 23, 87–105.

Lamoureux, S., 1994. Embedding unfrozen lake sediments for thin section preparation. Journal of Paleolimnology 10, 141–146.

Lamoureux, S., 1999. Spatial and interannual variations in sedimentation patterns recorded in nonglacial varved sediments from the Canadian high arctic. Journal of Paleolimnology 21, 73–84.

Lamoureux, S., 2000. Five centuries of interannual sediment yield and rainfall-induced erosion in the Canadian high arctic recorded in lacustrine varves. Water Resources Research 36, 309–318.

Lamoureux, S., 2001. Varve chronology techniques. In: Last, W., Smol, J. (Eds.), Tracking Environmental Change Using Lake Sediments, vol. 1. Kluwer Academic Publishers, Boston, MA, pp. 247–260.

Lamoureux, S., 2002. Temporal patterns of suspended sediment yield following moderate to extreme hydrological events recorded in varved lacustrine sediments. Earth Surface Processes and Landforms 27, 1107–1124.

Langbein, W.B., Schumm, S.A., 1958. Yield of sediment in relation to mean annual precipitation. Transactions of the American Geophysical Union 39, 1076–1084.

Leonard, E.M., 1997. The relationship between glacial activity and sediment production: evidence from a 4450-year varve record of neoglacial sedimentation at Hector Lake, Alberta, Canada. Journal of Paleolimnology 17, 319–330.

Loso, M., Anderson, R., Anderson, S., 2004. Post-Little Ice Age record of coarse and fine clastic sedimentation in an Alaskan proglacial lake. Geology 32, 1065–1068.

Madej, M.A., 1987. Residence times of channel-stored sediment in Redwood Creek, northwestern California. IAHS Publication 165, 429–438.

Major, J.J., Pierson, T.C., Dinehart, R.L., Costa, J.E., 2000. Sediment yield following severe volcanic disturbance — a two decade perspective from Mount St. Helens. Geology 28, 819–822.

Mann, M.E., Lees, J.M., 1996. Robust estimation of background noise and signal detection in climatic time series. Climatic Change 33, 409–445.

Menounos, B., 2002. Climate, fine-sediment transport linkages, Coast Mountains, British Columbia, Canada. Ph.D. thesis, University of British Columbia, Vancouver.

Meybeck, M., Laroche, L., Dürr, H.H., Syvitski, J.P.M., 2003. Global variability of daily total suspended solids and their fluxes in rivers. Global and Planetary Change 31, 191–199.

Minobe, S., 1997. A 50–70 year climate oscillation over the North Pacific and North America. Geophysical Research Letters 24, 683–686.

Pearce, A.J., Watson, A., 1983. Medium-term effects of two landsliding episodes on channel storage of sediment. Earth Surface Processes and Landforms 8, 29–38.

Pelpola, C.P., Hickin, E.J., 2003. Long-term bed load transport rate based on aerial-photo and ground penetrating radar surveys of fan-delta growth, Coast Mountains, British Columbia. Geomorphology 57, 169–181.

Pitlick, J., 1993. Response and recovery of a subalpine stream following a catastrophic flood. Geological Society of America Bulletin 105, 657–670.

Reasoner, M.A., 1993. Equipment and procedure improvements for a lightweight, inexpensive, percussion core sampling system. Journal of Paleolimnology 8, 273–281.

Richards, K., 1984. Some observations on suspended sediment dynamics in Storbregrova, Jotunheimen. Earth Surface Processes and Landforms 9, 101–112.

Richards, G., Moore, R.D., 2002. Suspended sediment dynamics in a steep, glacier-fed mountain stream, Place Creek, Canada. Hydrological Processes 17, 1733–1753.

Schiefer, E., Slaymaker, O., Klinkenberg, B., 2001. Physiographically controlled allometry of specific sediment yield in the Canadian Cordillera: a lake sediment-based approach. Geografiska Annaler Series A 83, 55–65.

Simon, A., 1999. Channel and drainage-basin response in the Toutle River system in the aftermath of the 1980 eruption of Mt. Saint Helens. USGS Open File Report, vol. 96–633. USGS (United States Geological Survey), Washington, D.C.

Slaymaker, O., 1977. Estimation of sediment yield in temperate alpine environments. IAHS Publication 122, 109–117.

Slaymaker, O., 1987. Sediment and solute yields in British Columbia and Yukon: their geomorphic significance re-examined. In: Gardiner, V. (Ed.), International Geomorphology, 1986 Part I. John Wiley & Sons, pp. 925–945.

Slaymaker, O., Souch, C., Menounos, B., Filippelli, G., 2003. Advances in Holocene mountain geomorphology inspired by sediment budget methodology. Geomorphology 55, 305–316.

Smith, D.G., 1998. Vibracoring: a new method for coring deep lakes. Palaeogeography, Palaeoclimatology, Palaeoecology 140, 433–440.

Smith, N.D., Ashley, G.M., 1985. Proglacial lacustrine environments. In: Ashley, G., Shaw, J., Smith, N. (Eds.), Glacial Sedimentary Environments. SEPM Short Course, vol. 16. Society of Paleontologists and Mineralogists, Tulsa, OK, pp. 135–215.

Thomas, R.B., 1985. Estimating total suspended sediment yield with probability sampling. Water Resources Research 21, 1381–1388.

Thompson, M.P., Joe, H., Church, M., 1987. Statistical Modeling of Sediment Concentration. Environment Canada Water Resources Branch Report IWD-HQ-WRB-SS-88-1. Ottawa.

Trimble, S.W., 1983. A sediment budget for Coon Creek Basin in the Driftless Area, Wisconsin, 1853–1977. American Journal of Science 283, 454–474.

Truhlar, J.F., 1978. Determining suspended sediment loads from turbidity records. Hydrological Sciences Bulletin 23, 409–417.

Walling, D.E., 1983. The sediment delivery problem. Journal of Hydrology 65, 209–237.

Walling, D.E., Fang, D., 2003. Recent trends in the suspended sediment loads of the world's rivers. Global and Planetary Change 39, 111–126.

Walling, D., Webb, B.W., 1982. Sediment availability and the prediction of storm-period sediment yield. IAHS Publication 137, 327–337.

Walling, D., Webb, B.W., 1996. Erosion and sediment yield: a global overview. IAHS Publication 236, 3–19.

Wallis, J.R, O'Connell, P.E., 1972. Small sample estimation of ρ_1. Water Resources Research 8, 707–712.

Ward, P., Skermer, N.A., 1992. The 50-year flood in Fitzsimmons Creek, Whistler, British Columbia. Geotechnique and Natural Hazards, A Symposium. Vancouver Geotechnical Society, Vancouver, BC, pp. 355–363.

Williams, G.P., 1989. Sediment concentration versus water discharge during single hydrologic events in rivers. Journal of Hydrology 111, 89–106.

Yevjevich, V., 1972. Probability and Statistics in Hydrology. Water Resources Publications, Fort Collins, Colorado.