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**A Multi-century Estimate of Suspended Sediment Yield from
Lillooet Lake, Southern Coast Mountains, Canada**

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A multi-century estimate of suspended sediment yield from Lillooet Lake

A Multi-century Estimate of Suspended Sediment Yield from Lillooet Lake, Southern Coast Mountains,
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Abstract

We use annually laminated lake sediments to estimate suspended sediment yield for a 3850 km² montane catchment in the British Columbia Coast Mountains. Sediment yield over the past 369 years averages $213 \pm 38 \text{ Mg km}^{-2} \text{ a}^{-1}$. Sediment yield increases to $285 \pm 50 \text{ Mg km}^{-2} \text{ a}^{-1}$ during the first half of the twentieth century and declines thereafter. The frequency of high-yield events during the 369-year period is irregular: 11 of the 34 events occur in the early part of the twentieth century, a time when glaciers in the watershed underwent major retreat. We fitted a Generalized Extreme Value (GEV) model to estimate quantiles of the sediment yield distribution, and we used epoch analysis to examine persistence in sediment yield following 34 of the largest events. Persistence is greatest for the most extreme events; it is more variable for events that recur, on average, every 10 to 25 years. Our results indicate that sediment yield is linked to long-term changes in sediment supply to the lake. The results of this study extend earlier sediment yield estimates and improve understanding of linkages to watershed geomorphology, recent glacier retreat, and landslides in the Lillooet River watershed.

Keywords:

Lillooet River, British Columbia, sediment yield, varves, glacial history, landslides

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1. Introduction

Specific sediment yield is the amount of sediment that leaves a watershed during a specified period, typically days or years; as opposed to basin-wide total yield, it is measured as mass per unit area per unit time (Onstad, 1984; Schiefer et al., 2010). Sediment yield studies are performed to assess sediment sources, production, transport, and storage within watersheds. These studies provide valuable information on the influences of glacier cover (Desloges, 1994), hydrology and climate (Lamoureux, 2002; Menounos et al., 2006), land-use changes (O'Hara et al., 1993; Zolitschka, 1998), landslides (Koi et al., 2008), and other landscape disturbances (Major et al., 2000) on long-term sediment export from mountain catchments, as well as the complex connectivity between sedimentary and geomorphic processes (Wohl et al., 2017).

Lacustrine sediments are ideal proxies of long-term suspended sediment yield because lakes trap clastic sediments derived from the upstream watershed (e.g., Zolitschka, 1998). Annually laminated (varved) lacustrine records offer an additional advantage because they provide insight into hydroclimatic and depositional conditions in the basin with annual to sub-annual resolution (Desloges and Gilbert, 1994; Lamoureux, 2000). Several studies in the Canadian Cordillera have used varved sediments to estimate suspended sediment yield in proglacial lakes (Desloges, 1994; Menounos et al., 2006; Schiefer et al., 2010).

Previous research documents sedimentation and sediment yield in the Lillooet River watershed, a 3850 km² mountain watershed in the southern Coast Mountains of British Columbia, Canada (Figure 1). Gilbert (1972, 1973, 1975) inferred sedimentary and lacustrine processes responsible for the distribution and character of sediments in Lillooet Lake. He estimated average total clastic sediment yield in the Lillooet River watershed to be 334 Mg km⁻² a⁻¹. Gilbert (1975) further showed that the lake sediments are annually laminated (varved) and that varve thickness is related to Lillooet River discharge. Jordan and

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Slaymaker (1991) used a sediment budget approach to determine sources, storage, and yield of sediment in the Lillooet River watershed. They found that Holocene sediment input is highly episodic and that colluvial and glacial sediment sources are likely underestimated. Recurrent mass movements off the Mount Meager volcanic complex (Friele and Clague, 2004), changes in glacier cover (Desloges and Gilbert, 1994), and the formation of Silt Lake in the forefield of Lillooet Glacier at the head of the watershed (Schiefer and Gilbert, 2008) could explain the imbalance that Jordan and Slaymaker (1991) found in their sediment budget.

In this paper, we report on a multi-century record of specific suspended sediment yield from the Lillooet River watershed based on analysis of cores collected from Lillooet Lake. Our objective is to provide, on a timescale of hundreds of years, a better understanding of (1) changes in sediment export from a mountain watershed in which sediment production is dominated by changes in glacier cover, landslides, and floods, and (2) the connectivity between sediment sources and processes and sediment accumulation in the lake. Years with exceptionally high yields are identified, and we attempt to explain conditions that could account for these anomalous years. We also consider annual and decadal impacts of glacier activity and known pre-historic and historic landslides in the watershed on the production and delivery of suspended sediment to Lillooet Lake. The results of this study provide a long-term perspective of the importance of landslides and glacier cover on specific sediment yield in the Canadian Cordillera.

2. Study site and methods

Lillooet Lake is an oligotrophic dimictic lake with a length of 22 km, a width up to 2 km, and a maximum depth of 137 m (Figure 1; Desloges and Gilbert, 1994). About 14% of the watershed is covered by glacier ice and persistent snow. Peaks in the watershed reach up to 2700 m above sea level (asl),

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88 whereas the broad flat floor of Lillooet River valley ranges from about 200 m asl at Lillooet Lake to 820 m
89 asl at the toe of Lillooet Glacier.

90 The climate station at Pemberton Airport receives, on average, 890 mm of water-equivalent
91 precipitation annually, mainly during autumn and winter (Environment Canada, 2011). Higher elevations
92 in the watershed likely receive over 3000 mm water-equivalent precipitation each year (Pacific Climate
93 Impacts Consortium, 2016).

94 Lillooet River is the dominant source of water and sediment to Lillooet Lake. The river heads at
95 Lillooet Glacier about 95 km northwest of Lillooet Lake. Silt Lake, a large proglacial lake, lies about 2 km
96 beyond the present terminus of Lillooet Glacier. The principle tributaries of Lillooet River are Meager
97 Creek, and Ryan, Birkenhead, and Green rivers (Figure 1). Mean annual discharge of Lillooet River is 126
98 $\text{m}^3 \text{s}^{-1}$ based on a record of discharge that exceeds 90 years. In a typical year, the river experiences a nival
99 melt peak of 400-600 $\text{m}^3 \text{s}^{-1}$ in June and a similar-size peak related to snow and glacier ice melt in July
100 (Environment Canada, 2010). Floods with peak discharge up to 1370 $\text{m}^3 \text{s}^{-1}$ (in 2003) occur in the fall
101 during intense rain or rain-on-snow storms.

102 Most of the sediment deposited in Lillooet Lake is delivered by Lillooet River (Desloges and Gilbert,
103 1994). Concentrations of suspended sediment discharged into Lillooet Lake vary throughout the year. In
104 winter, when discharge is lowest, suspended sediment concentrations are as low as 5 mg l^{-1} , whereas during
105 nival and glacial melt in late spring and summer they are 600-800 mg l^{-1} , and during floods they are over
106 1200 mg l^{-1} (Gilbert, 1975; Hodder, 2009).

107 Lillooet River drains mainly Mesozoic granitic and metamorphic rocks (Read, 1979). However, the
108 Mount Meager Volcanic Complex, located in the upper part of the watershed (Figure 1), comprises
109 andesitic and dacitic lavas and pyroclastic rocks of Plio-Pleistocene and Holocene age. The most recent

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eruption from this massif happened about 2400 years ago (Clague et al., 1995). Some of the volcanic rocks have been hydrothermally altered and are highly susceptible to landslides (Mokievsky-Zubok, 1977; Read, 1990; Friele and Clague, 2004; Guthrie et al., 2012). Landslides are common on the flanks of the volcanic massif and range from rare flank collapses with volumes of hundreds of million cubic metres (Friele and Clague, 2004) to small debris flows that occur every year during hot weather or rain. The most recent large landslide happened in 2010 in the headwaters of Capricorn Creek, a tributary of Meager Creek (Roche et al., 2011; Guthrie et al., 2012). This landslide delivered about $48.5 \times 10^6 \text{ m}^3$ of debris to the valleys of Meager Creek and Lillooet River and stemmed the flow of both streams for a short time.

We collected three percussion cores and nine vibracores from Lillooet Lake during the summers of 2005 and 2006 (Figure 1). The cores were collected throughout the lake basin in water depths ranging from 78 to 128 m; the cores have lengths that range from 1.8 m to 11.1 m (limitations in the results due to core location are discussed below). We split, logged, and photographed the cores and sampled them at a 10-cm interval for bulk density and grain size analysis. Desloges and Gilbert (1994) and Menounos et al. (2005) found low (<1%) concentrations of organic matter in their cores from the lake, and so we use 5% as a conservative measure of organic content. We identified and digitally measured silt-clay couplets, which Gilbert (1973, 1975), Desloges and Gilbert (1994), and Heideman et al. (2015) demonstrated to be varves, with a resolution of 0.1 mm using Gimp2 (2012) software to determine sedimentation rates (SR).

To estimate sediment yield, we first calculated the average sedimentation rate (SR_i) in each core (i) as the product of the accumulation rate (AR_i) and dry density (DD_i):

$$SR_i (\text{kg m}^{-2} \text{a}^{-1}) = AR_i (\text{m a}^{-1}) \times DD_i (\text{kg m}^{-3}) \quad (\text{eq. 3.1})$$

Thiessen (Voronoi) polygons were used to represent contributing areas for a given core. We computed sediment mass (M_i) by multiplying sedimentation rates by core polygon area ($Area_i$):

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$$M_i (kg a^{-1}) = SR_i (kg m^{-2} a^{-1}) \times Area_i (m^2) \quad (eq. 3.2)$$

To build the varve chronology, we identified and traced distinctive varves from core to core; the ones that were disturbed were excluded from sediment yield calculations. For these years, we estimated sediment yield by assuming that sedimentation rates in neighbouring cores are representative of those in the excluded core and by thus merging the Thiessen polygon with its closest neighbour(s).

We then calculated total sediment mass for each year by summing the masses of contributing cores for that year. Finally, we calculated suspended sediment yield (Y_y) for each year (y) by dividing the total sediment mass (M_{tot}) by the catchment area (CA):

$$Y_y (kg km^{-2} a^{-1}) = M_{tot} (kg a^{-1}) / CA (km^2) \quad (eq. 3.3)$$

Sediment yields are reported as megagrams ($Mg km^{-2} a^{-1}$) in this study. Absolute sediment yield estimates are indicated by 'Y'. Recurrence intervals of specified sediment yields are reported, for example as Y_{10} or Y_{10-25} , denoting sediment yields with, respectively, recurrence intervals of once every ten years and once every ten to 25 years.

Errors in sediment yield values arise from each of the above-mentioned steps in the procedure: varve thickness measurements, dry density estimates, and Thiessen polygons that assume an area of equal sedimentation rates around each core. Error is also introduced from our estimate of organic matter and from the limited number of cores contributing to the chronology.

To estimate varve thickness error, we re-measured five to eight consecutive varves in undisturbed, well correlated sections of each core. The average difference in measurements is 6.1%, which we took to be the varve thickness error. Maximum errors stemming from missing and false varves are 1.61% (Heideman et al., 2015), and we include this error term in our sediment yield uncertainty estimates. We did

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not replicate dry density measurements; rather we used the standard deviation for each core ($\pm 1\sigma$) to derive an error estimate for this variable. The resulting estimate of error in dry density measurements is 11.2%, and our uncertainty (standard deviation) for the organic content of the sediments is 10.9%.

We estimated error related to the number of cores contributing to the calculation of total sediment yield for the period AD 1629-1997 by comparing the difference in yield between estimates based on 10 or 11 cores (i.e. the maximum number of cores contributing to the chronology in a given year) and estimates based on the five cores that make up the chronology up to AD 1629. This error is 5.5%.

The use of Thiessen polygons assumes that sediment deposition is spatially uniform throughout each polygon. The polygons, however, underestimate sedimentation in places like the delta front, the lake shoreline, and steep slopes on the lake bottom (Gilbert, 1975; Jordan and Slaymaker, 1991). Schiefer (2006), for example, estimated that deltaic sediments in nearby Green Lake cover approximately 10% of the total lake-bottom area and that massive and weakly laminated deposits constitute about 13% and 19%, respectively, of the lake bottom. Varved sediments in Green Lake are thus present on only 58% of the total lake floor. Although Green Lake and Lillooet Lake differ considerably in size (2.0 km² vs. 35 km²) and depth (44 m vs. 137 m), both have similar bathymetries (Schiefer and Klinkenberg, 2004). Previous studies (Gilbert, 1973, 1975; Gilbert and Desloges, 1994) offer useful information on bottom sediments in Lillooet Lake, but do not provide a lake-wide quantitative spatial inventory. Weakly laminated sediments are recorded in proximal cores C and D in Lillooet Lake (Figure 1). Sedimentation north of core D (Figure 1) is likely underestimated and occurs over nearly 25% of the total area of the lake bottom. Because the number of cores used in this study is limited and no cores were taken on the delta front, it is not possible to precisely quantify the error related to spatial differences in sedimentation. In-lake sedimentation processes (e.g., lake stratification, sediment movement in overflows and underflows, water column turn-over, and

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flocculation [Gilbert, 1975; Hodder, 2009]), and the timing of floods can also affect sediment distribution and accumulation in the lake.

We adopt standard error propagation methods that are suitable for measurements of terms found in equations 3.2 and 3.3 (Taylor, 1982). Total error in suspended sediment yield from errors in dry density, varve thickness, organic content, varve counting error, and the number of cores contributing to the yield is estimated to be $\pm 17.7\%$.

3. Results

3.1. Sediment yield statistics

The varve sequence retrieved from Lillooet Lake extends from AD 1179 to 2004 (Heideman et al., 2015). Sediment yield appears to be below the long-term average from the beginning of the record to around AD 1629 (Figure 2). The early part of the record, however, is based on only two cores (A and B), both of which originate from the distal basin. The distal cores in Lillooet Lake have lower sedimentation rates than cores from the proximal basin. To test whether this bias could be removed, we regressed the average sediment mass accumulation in cores A and B (the cores with the longest records) with the total basin yield for the period AD 1629-2004. The explained variance is poor ($r^2 = 0.044$, $p < 0.05$), which indicates that sedimentation at the two distal cores sites is not representative of total sediment yield in the basin. We therefore excluded years prior to AD 1629 from further analysis. Likewise, the sediment yield record for the period 1998-2004 is based on one to three cores and was similarly excluded from further analysis.

Sediment yield for the period AD 1629-1997 ranges from 74 to 672 $\text{Mg km}^{-2} \text{a}^{-1}$; the long-term average value is $213 \pm 38 \text{ Mg km}^{-2} \text{a}^{-1}$ (Table 1, Figure 3). Minimum and maximum values for the

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twentieth century are similar to the long-term values, $77 \text{ Mg km}^{-2} \text{ a}^{-1}$ (AD 1916) and $659 \text{ Mg km}^{-2} \text{ a}^{-1}$ (AD 1906), but the average for this period is 11% greater ($234 \pm 42 \text{ Mg km}^{-2} \text{ a}^{-1}$) than the long-term average and is the highest centennial average for the period of record. In addition, the average for the first half of the twentieth century (AD 1900-1945) is much higher than the average for the second half of the century (AD 1946-1997): 285 ± 50 vs. $183 \pm 32 \text{ Mg km}^{-2} \text{ a}^{-1}$.

We calculated general descriptive statistics for the sediment yield data for the period AD 1629-1997 (Table 1). The statistics imply a strongly non-normal distribution of sediment yield estimates, with the maximum sediment yield estimate exceeding the mean by over three times. Extreme value distributions, such as Gumbel, Fréchet, and Weibull, are typically used in paleoflood hydrology studies (e.g. Hosking and Wallis, 1986) to estimate the upper quantiles of a probability distribution. We therefore fitted a generalized extreme value model (Jenkinson, 1955) — a flexible model that estimates the three parameters determining the Gumbel, Fréchet, and Weibull distributions — to estimate yield quantiles and return intervals for outliers in the AD 1629-1997 sediment yield chronology. The resulting GEV model had a resulting shape parameter of $k > 0$ and can thus be classified as a GEV type II or Fréchet-type distribution (c.f. Lamoureux, 2002).

We determined recurrence times of peaks in the sediment yield record using a generalized extreme value model (GEV type II). Years of high sediment yield ($>Y_{10}$) are unevenly distributed in the 369-year record (Figures 4 and 5): 13 of the 34 peaks are in the twentieth century (Table 2). Peaks in sediment yield with an average return period greater than once every 10 years exceed the AD 1629-1997 mean yield by 1.6 to 3.1 times (Figure 4). Peaks in sediment yield with an average return period of more than 25 years ($>Y_{25}$) cluster around AD 1776-1825 and AD 1906-1931; the intervening period lacks such extremes and includes only five peaks with an average return period ranging from 10 to 25 years (Y_{10-25}). Another

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striking characteristic of the AD 1629-1997 sediment yield record is the above-average yield from around AD 1920 to 1946, but much lower yields after AD 1946.

3.2. *Long-term sediment-yield departures*

Cumulative sediment-yield departures demonstrate the effect of high-yield years on sediment delivery in subsequent years (Lamoureux, 2002). The sediment yield record for Lillooet Lake has five periods with negative trends: AD 1629-1696, 1729-1768, 1777-1792, 1826-1881, and 1945-1997 (Figure 5). The onset of each of four subsequent positive-trending periods (AD 1697-1728, 1769-1776, 1793-1825, 1882-1944), however, is not a high-yield ($>Y_{10}$) year. Instead, high-yield years ($>Y_{10}$) typically occur three to five years following the start of a positive-trending period.

Negative-trending periods contain 11 high-yield years ($>Y_{10}$), which constitute 234 of the 369 years of the record. In contrast, 23 such events happen during positive-trending periods (135 years). Sediment yields with return periods greater than 50 years only occur during positive-trending periods.

In many instances, high-yield years are 'stand-alone' events. Some of these stand-alone years are immediately followed by a negative trend in cumulative sediment yield, for example after AD 1647, 1661, and 1991. In contrast, a positive trend for two decades follows the high-yield years of AD 1712, 1713, and AD 1921.

Two of the highest yield years, both of which have estimated return periods greater than 100 years (AD 1776, 1825), are separated by only 49 years and occur at the end of a period of positive-trending years. After AD 1825, cumulative sediment yield has a negative trend that persists until AD 1881, followed by a 63-year period with a positive trend until AD 1946. Twelve high-yield events ($>Y_{10}$) occur during the period AD 1881-1946, of which three have return periods greater than 100 years.

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These results show that the highest yield years are not necessarily followed by long periods (e.g. more than a decade) of above-average yields. Only two smaller yield years (i.e. AD 1712 and 1713) precede intervals of above-average sediment yield spanning about three decades (Figure 5).

3.3. *Sediment yield trends following high-yield years*

The Lillooet Lake sediment yield record includes 34 years with estimated return periods greater than 10 years (Table 2). Examination of cumulative departures in the 30 years immediately after each high-yield year ($>Y_{10}$) reveals highly variable sedimentation patterns (Figures 7 and 8). Two years with the highest yields ($>Y_{100}$; AD 1921 and 1931) are followed by prolonged periods of above-average yield (Figure 6a). The high yields of AD 1921 and 1931 are followed by above-average yields in 1936 and 1940. The average trends in the Y_{50-100} and Y_{25-50} groups (Figure 6b and 6c) are positive for the first 12 and 10 years, respectively. Individual signals of years AD 1823 (Y_{50-100}), 1774 (Y_{25-50}), and 1936 (Y_{25-50}) are influenced by much larger events two to four years later (i.e. AD 1825, 1776, and 1940, respectively). The common pattern in the Y_{10-25} group is above-average sediment yield immediately after event years (Figure 7), but there are many exceptions. The events in the seventeenth century are noteworthy: all show a negative trend following the high-yield year. The other centuries show more variable trends after high yield events.

3.4. *Persistence of high-yield years*

To further assess the impact of high-yield years on subsequent sedimentation in Lillooet Lake, we superposed the years in each quantile group. For each high-yield year, we calculated the deviation from the 40-year mean for 10 years prior to and 30 years after each event (Panofsky and Brier, 1958; Lamoureux, 2002). The significance of high-yield years ($>Y_{10}$) was tested using the ‘sea’ command in the dplR package of the statistical program R, in which randomly selected years were bootstrap resampled to determine the significance of departures from the mean. No persistence of high-yield years is evident over the entire

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length of the record, but weak relations are apparent for specific sediment yield groups (i.e. $> Y_{10}$, Y_{25-50} , Y_{50-100} , Y_{100}).

All high-yield years ($> Y_{10}$) have significant ($p < 0.05$) departures from the mean. Persistence is evident in two of the first five years immediately after all 34 events (Figures 8b and 8c), although deviations from the mean are small ($< 50 \text{ Mg km}^{-2} \text{ a}^{-1}$). For years with a return period greater than 100 years (Figure 8a), the first year after the event has above-average sediment yield, but that year is followed by four years with below-average yields. In the case of the Y_{50-100} group, positive deviations from the mean are evident in four of the first five years after the high-yield year, but subsequent years show more negative deviations from the mean than positive deviations. The Y_{25-50} group (Figure 8c) shows an initial positive deviation from the mean, followed by mainly below-average yields after four years. Similarly, the Y_{10-25} group (Figure 8d) has an initial positive deviation in the first year, with slightly positive and negative deviations after that.

The Y_{50-100} and Y_{25-50} groups display above-average yields in, respectively, five and eight of the ten years prior to the high-yield year. The other two groups have more negative years leading up to the high-yield year.

Persistence in high-sediment yields is more pronounced in the twentieth century in the Y_{50-100} and Y_{25-50} quantile groups than in the other groups. However, 13 of the 34 high-yield years are in the twentieth century, and 11 of those 13 years are in the period AD 1900-1946, which is a period of above-average sedimentation (Figure 3). It is therefore difficult to draw conclusions about persistence of sediment yield in the twentieth century, because high-yield events ($> Y_{10}$) occur on average every 4.2 years in the first 46 years of the century, and any persistence in the system is masked by subsequent, possibly unrelated, high-yield events. In comparison to the persistence pattern for the entire 369-year record (Figure 8), there are a

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larger number of years with positive deviations in the twentieth century (Figure 9), but this too can be attributed to the frequency of high-yield years in the first half of the century.

4. Discussion

4.1. Comparisons to other sediment yield studies in western Canada

The long-term (AD 1629-1997) average suspended sediment yield estimate ($213 \pm 38 \text{ Mg km}^{-2} \text{ a}^{-1}$) for the period AD 1629-1997 (Table 3) is similar to the estimate of Desloges and Gilbert (1994) based on their study of Lillooet Lake, but less than those of Slaymaker (1972) and Gilbert (1973).

Church and Slaymaker (1989) argue that sediment yield in British Columbia increases as a function of watershed area in catchments up to $3 \times 10^4 \text{ km}^2$ in area. This conclusion is supported by sediment yield estimates derived from cores extracted from Harrison Lake (Desloges and Gilbert, 1991), Green Lake (Menounos et al., 2006; Schiefer et al., 2010), Chilko Lake (Desloges and Gilbert, 1998), Bowser Lake (Gilbert et al., 1997), Moose Lake (Desloges and Gilbert, 1995), and smaller lakes in the Canadian Cordillera (Desloges, 1994; Schiefer et al., 2001; Schiefer and Gilbert, 2008). Long-term suspended sediment yield estimates derived from the Lillooet Lake data (Figure 10) fall within the expected sediment yield pattern in British Columbia.

Sediment yield in the Lillooet River watershed in the twentieth century was likely affected by many events, notably landslides, floods, glacier retreat, the formation of Silt Lake, river engineering, and land-use changes in the watershed. In comparison, the watershed of nearby Green Lake before the establishment of the Whistler ski resort in the 1960s was largely undisturbed and was not subject to river straightening or dyking (Menounos et al., 2006). Sediment yield in the Green Lake watershed before the 1960s thus reflects more natural conditions. Suspended sediment yield, as derived from varved sediments, in Green Lake

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during the period 1931-1991 is 10% higher than during the past 3000 years (Menounos et al., 2006): ca. 76 $\text{Mg km}^{-2} \text{a}^{-1}$ vs. 69.4 $\text{Mg km}^{-2} \text{a}^{-1}$. Menounos et al. (2006) attributed the higher sediment yield during the twentieth century to increased sedimentation accompanying retreat of glaciers between 1935 and 1945, although human disturbances in the watershed between about 1960 and 1991 may also have played a role.

Schiefer et al. (2010) extended the work of Menounos et al. (2006) in Green Lake. They studied lake sediment cores, delta progradation, and solute transport, and concluded that the average annual total sediment yield since the mid-1900s has been $320 \pm 40 \text{ Mg km}^{-2} \text{a}^{-1}$, of which about 35% is suspended load, 50% is bedload, and 15% is dissolved load. The ratios of the three components of sediment yield, however, differ significantly on a decadal time scale, which could have important consequences if short-term values are used to estimate long-term sediment yields. Similarly, Loso et al. (2004) reported that suspended sediment is less than 20% of the total clastic sediment discharge into Alaskan proglacial Iceberg Lake. If the sediment yield fractions for Green Lake are applicable to Lillooet Lake, and assuming constant ratios through time, total clastic sediment yield to Lillooet Lake would be $671 \pm 119 \text{ Mg km}^{-2} \text{a}^{-1}$ during the twentieth century and $612 \pm 108 \text{ Mg km}^{-2} \text{a}^{-1}$ for the period AD 1629-1997. However, these estimates should be viewed with care given the differences in the area and hypsometry of the two watersheds, the ratio of lake area to catchment area, and possibly other factors. Studies by Schiefer et al. (2010) and Loso et al. (2004) indicate that estimates of total clastic sediment yield based solely on the suspended sediment fraction may be misleading in some environments.

Considerable reductions in sediment yield in the second half of the twentieth century characterize ice-marginal Ape Lake in the central Coast Mountains and proglacial Berg Lake (Desloges, 1994) and Hector Lake (Leonard, 1997) in the Rocky Mountains. Varve-based sediment yield records from the first two lakes show declining sedimentation throughout the twentieth century, with a further abrupt decrease after AD

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1955. Desloges (1994) attributed this decrease to reduced glacial input following retreat of glaciers from Little Ice Age maxima. This reduction in sediment delivery is to be expected because the area of the bed over which temperate glaciers slide is reduced (Hallet et al., 1996). Lower sedimentation rates are also expected as recently deglaciated forefields, which are important sources of fine-grained sediments, become stabilized. Desloges (1994) also attributed reductions in clastic sediment delivery, in some instances, to the formation of proglacial lakes within glacier forefields.

4.2. Role of sediment sources and storage in persistence in the sediment-yield record

Our results indicate that there is some persistence in the sediment yield record from Lillooet Lake. Cumulative sediment yields after the most extreme events ($>Y_{100}$) differ, but generally increase (Figure 6). Sediment yield remains higher than the 40-year average up to one year after each event larger than Y_{25} (Figure 7). The persistence of high yields, however, probably depends on time-varying hydrological conditions in the watershed. Coarse-grained sediment mobilized during an extreme event may persist in the fluvial system for several years in bars in river channels or easily eroded river banks. Thereafter, hydrological conditions within the watershed determine whether large amounts of sediment will continue to be mobilized. These conclusions are consistent with Lamoureux's (2002) observations that suspended sediment is rapidly transported and that suspended sediment yield after an extreme event is less sensitive than bedload yield to channel aggradation and degradation.

Reports and dates are available for major twentieth-century events (e.g. landslides and floods) that may have impacted sediment yield in the Lillooet River watershed. These data allow us to better interpret historic high-yield events. Persistence in the twentieth century is, however, difficult to evaluate (Figure 9), because high-yield events in the first half of the century happened, on average, once every 4.2 years. As discussed below, the high frequency of extreme-yield events during the first half of the twentieth century is

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likely due to greater sediment availability resulting from glacier retreat from Little Ice Age maximum positions.

4.3. Interpretation of sediment-yield signal

Jordan and Slaymaker (1991) provide a conceptual model for Holocene sediment transport in glaciated mountainous watersheds based on their study of the Lillooet River watershed. They concluded that Neoglacial deposits, debris flows, and landslides are the main sediment sources in the watershed. Here, we consider the sediment-yield record from Lillooet Lake in terms of the sedimentary, geomorphic, and anthropogenic processes operating within the Lillooet River watershed in the past. Each of these processes can independently contribute to the sediment-yield signal, but they are interconnected and thus must be considered together. For example, climate warming can cause glaciers to retreat, increasing stores of sediment that are easily entrained and delivered to the fluvial system (Menounos et al., 2006; Menounos and Clague, 2008), while leaving newly deglaciated slopes unstable and vulnerable to erosion landslides or failure.

A consistent picture of late Holocene glacier activity in the southern Coast Mountains has emerged from studies in this region (Larocque and Smith, 2003; Reyes and Clague, 2004; Menounos et al., 2004; Allen and Smith, 2007; Koch et al., 2007, 2009; Clague et al., 2009, Mood and Smith, 2015). In Garibaldi Provincial Park about 35-40 km southwest of Lillooet Lake, an early Little Ice Age advance in the twelfth century was followed by glacier recession in the thirteenth century (Koch et al., 2007). Glaciers advanced several times in the fourteenth and fifteenth centuries, and achieved their maximum Holocene extents between AD 1690 and 1720 (Koch et al., 2007). Glaciers in Garibaldi Park and elsewhere in the southern Coast Mountains did not commence substantial retreat until the beginning of the twentieth century (Figure 11). Similarly, farther north, in the Pacific Range of the Coast Mountains, glaciers advanced between 800

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and 400 years ago (Mood and Smith, 2015). They reached their maximum positions in the late seventeenth or early eighteenth century and began to retreat in the early twentieth century. A similar pattern of late Holocene glacier advance and retreat has been documented in the Rocky Mountains and in the mountains of Alaska and Washington State (Mood and Smith, 2015).

Sediment yield in the Lillooet River watershed, although high throughout the period AD 1629-1997, increases from an average of $175 \pm 31 \text{ Mg km}^{-2} \text{ a}^{-1}$ in the seventeenth century to $235 \pm 42 \text{ Mg km}^{-2} \text{ a}^{-1}$ in the twentieth century. This increase coincides with the episodic expansion of alpine glaciers to their Little Ice Age maximum positions. The start of the twentieth century marks the beginning of the period with the highest sediment yields – the average yield for the period AD 1900-1945 is $285 \pm 50 \text{ Mg km}^{-2} \text{ a}^{-1}$. A comparable increase in sediment yield in the early twentieth century has been documented at nearby Green Lake (Menounos et al., 2006) and Cheakamus Lake (Menounos and Clague, 2008). These increases are attributed to availability of sediments following rapid retreat of glaciers from their Little Ice Age maximum positions.

Landslides, especially those originating from the Mount Meager massif, are also important sediment sources. Two prehistoric landslides (Friele et al., 2008) in the headwaters of Meager Creek (Figure 1) have calibrated radiocarbon age ranges of AD 1690-1790 and 1740-1860 (2- σ ranges). The ages of these events overlap with the age of two years of extreme sediment yields ($>Y_{100}$), dated to AD 1776 and 1825. The year with the tenth largest sediment yield (AD 1713; Y_{50-100} category) is also within the age range of the AD 1690-1790 landslide. The AD 1825 varve has no distinct sedimentological features other than being thicker than average, but the AD 1713 and 1776 varves contain a thick sub-annual lamina. The AD 1776 varve also has a distinctive yellow colour in distal cores and a thick dark silt bed in proximal cores. This event bed can be correlated with ease from core to core, and the distinctive yellow colour, possibly

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indicative of fine volcanic sediment derived from Mount Meager, is faintly visible in the most distal core (core E, Figure 12). The AD 1931 varve has a similar sedimentological signature (Figure 12); it coincides with a debris flow with a volume of $3 \times 10^6 \text{ m}^3$ that descended Devastation Creek, near Mount Meager, that year (Friele et al., 2008). Suspended sediment yield after these prehistoric extreme events remains higher than the 40-year average up to one year after the event, indicative of rapid transport of sediment to Lillooet Lake.

Friele et al. (2008) reported at least eight landslides with volumes larger than 10^5 m^3 in the Mount Meager Volcanic Complex during the twentieth century. Two of largest historic landslides, in AD 1931 ($3 \times 10^6 \text{ m}^3$; see above) and 1975 (10^7 m^3), coincide with peaks in the sediment yield record. Other historic landslides in the Lillooet River watershed did not have an immediate effect on sedimentation in Lillooet Lake, although a series of small landslides between AD 1986 and 1990 (Figure 13) may have preconditioned the watershed for the high sediment yields following a large flood in AD 1991.

There is a notable decrease in sediment yield after AD 1946 (Figure 13). We consider the possibility that the formation of Silt Lake or engineering works on Lillooet River are responsible for this decrease. Proglacial Silt Lake began to form at the toe of Lillooet Glacier sometime between AD 1947 and 1962 (Schiefer and Gilbert, 2008). As the glacier continued to retreat, the lake rapidly grew in size and trapped an increasing amount of suspended sediment ($10^3 \text{ Mg km}^{-2} \text{ a}^{-1}$) that would otherwise have been transported to Lillooet Lake. To evaluate the effect that Silt Lake has on sedimentation in Lillooet Lake, we considered the extreme possibility that all upstream sediment bypasses Silt Lake. In this scenario, an additional 1.23% of suspended sediment reaches Lillooet Lake; this amount is within the error range of our sediment yield estimate. It is thus improbable that changes in Silt Lake sediment storage significantly altered sediment yields in the second half of the twentieth century. Major engineering works were undertaken in Lillooet

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River valley in AD 1946 in response to a large flood in AD 1940. Sections of Lillooet River were straightened and dyked and the level of Lillooet Lake was lowered 2.5 m between 1946 and 1952 (Jordan and Slaymaker, 1991). The geomorphological and fluvial responses to these changes included down-cutting and bank erosion by Lillooet River and an increase in the rate of advance of the Lillooet River delta (Jordan and Slaymaker, 1991). Although the delta front advanced rapidly during the first five years after the engineering works were completed, the amount of suspended sediment deposited farther south in the lake does not appear to have increased (Figure 13).

5. Conclusions

We use an 825-year varve chronology, first examined by Heideman et al. (2015), to calculate and analyze sediment yields from the Lillooet River watershed. Cores nearest the Lillooet River delta span only part of the 825-year record and thus limit our sediment-yield estimates to the period AD 1629-1997. Our estimate of average suspended sediment yield for this 369-year period is $213 \pm 38 \text{ Mg km}^{-2} \text{ a}^{-1}$, comparable to the previous estimate of Desloges and Gilbert (1994). High sediment-yield years are unevenly distributed over the period – 13 of 34 extreme yield years are in the twentieth century, and 11 of the twentieth-century extreme yield years were before AD 1946.

High sediment yields in the seventeenth, eighteenth, and nineteenth centuries coincide with the time of maximum Little Ice Age glacier cover in the watershed. We attribute increased sedimentation in Lillooet Lake in the early part of the twentieth century to enhanced mobilization and delivery of glacial sediments to the lake following glacier retreat. Lower average sediment yields in the second half of twentieth century appear to result principally from stabilization of recently deglaciated terrain by vegetation and river training.

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Peaks in sediment yield in the second half of the twentieth century have complex relations with Lillooet River discharge and major landslides at Mount Meager (Figure 13). For example, a large historic landslide in 1975, which occurred shortly before a high flow event on Lillooet River, produced a varve that is only in the Y_{10-25} category. In contrast, the thick 1991 varve (Y_{25-50}) is attributed to a series of landslides in years leading up to 1991, in combination with the one of the largest Lillooet River floods on record.

We interpret the sediment-yield record in Lillooet Lake in terms of the complex connectivity among a variety of sediment sources and climatic, geomorphic, and anthropogenic processes, among which glacier activity, landslides, and river engineering play a role. The variety of processes that shape the mountainous Lillooet River watershed makes it difficult to disentangle causative events; as a result, interpretations of specific annual yields remain inconclusive. In addition, our estimates of sediment delivery to Lillooet Lake do not include bedload, thus there are large uncertainties in total clastic yield to the lake. Nevertheless, variations in the suspended sediment component of the total clastic yield are consistent with what is known about the regional glacial and landslide history of the watershed.

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Tables

Table 1. Sediment yield estimates (in tonnes km⁻² a⁻¹) for the entire period of record (AD 1179-1629) and 1629-1997.

Period	AD 1179-2004	AD 1179-1628	AD 1629-1997
Mean (±1 standard deviation)	158.9 ± 28	111.4 ± 20	213.1 ± 38
Minimum	35.5	35.5	74.3
Maximum	1184.1	1184.1	672.3

Table 2. Number of years with sediment yields greater than specified estimated return periods.

Century (AD)	Return period				Total
	>Y ₁₀₀	Y ₅₀₋₁₀₀	Y ₂₅₋₅₀	Y ₁₀₋₂₅	
1900-1997	3	1	3	6	13
1800-1899	1	1	-	5	7
1700-1799	1	1	1	6	9
1629-1699	-	1	1	3	5
Total	5	4	5	20	34

Note: >Y₁₀₀ = sediment yield (Y) with an estimated return period greater than once every 100 years; Y₅₀₋₁₀₀ = sediment yields with estimated return periods between 50 and 100 years; etc.

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614 *Table 3. Comparison of sediment yield estimates derived from this (AD 1629-2004) and other published*
 615 *studies.*

Study	This study	Slaymaker (1972)	Gilbert (1973)	Desloges and Gilbert (1994)
Sediment yield (Mg km ⁻² a ⁻¹) ^a	213	386	334 ^b	188-218
Component of total sediment yield	Average annual long-term suspended sediment yield	Suspended load	Annual suspended load	Annual total basin yield, fine fraction ^c
Estimate derived from	Varves	?	Varves and pro-delta sediments	Varves
Original reported yield		1450×10^3 tonnes a ⁻¹	1.1×10^6 m ³ a ⁻¹	$6.2-7.2 \times 10^5$ m ³ a ⁻¹
Period	AD 1629-1997	?	AD 1913-1969	AD 1864-1988

616 ^a Estimates recalculated to Mg km⁻² a⁻¹ to compare with the results of this study.

617 ^b Gilbert (1973) estimated the volume of sediment accumulating on the pro-delta to be 5.3×10^7 m³ and in
 618 the rest of the lake 6.3×10^6 m³ for the period 1913-1969 (total 1.1×10^6 m³ a⁻¹, equivalent to 334 Mg km⁻²
 619 a⁻¹).

620 ^c Total basin yield of the fine fraction (< 63 µm). Desloges and Gilbert (1994) estimated the total basin
 621 yield (fine and coarse fraction) to be $15.5-16.5 \times 10^5$ m³ a⁻¹, equivalent to 472-501 Mg km⁻² a⁻¹.

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Figure Captions

Figure 1. Map of the Lillooet Lake watershed. Inset left: bathymetry of Lillooet Lake and core locations.

Figure 2. Sediment yield record derived from Lillooet Lake sediments for the period AD 1179-2004.

Figure 3. Sediment yield record derived from Lillooet Lake sediments for the period AD 1629-1997.

Figure 4. Estimated return periods for sediment yield estimates, AD 1629-1997, based on a generalized extreme value (GEV) distribution (numbers in black are years with return periods greater than once every 25 years).

Figure 5. Cumulative departure of sediment yield for the period AD 1629-1997.

Figure 6. Cumulative departure from AD 1629-1997 mean sediment yield for each group of recurrence interval group (6a: $>Y_{100}$; 6b: Y_{50-100} ; 6c: Y_{25-50}).

Figure 7. Cumulative departure from AD 1629-1997 mean sediment yield for events with a recurrence interval between 10 and 25 years (Y_{10-25} ; 7a = seventeenth century; 7b = eighteenth century; 7c = nineteenth century; 7d = twentieth century; black = average cumulative departure of all Q_{10-25} events).

Figure 8. Deviations from the mean over the period extending from 10 years before to 30 years after each

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high-yield year for groups with different recurrence intervals over the period AD 1629-1997. Red column is event year '0'.

Figure 9. Deviations from the mean over the period extending from 10 years before to 30 years after each high-yield year for groups with different recurrence intervals over the twentieth century. Red column is event year '0'.

Figure 10. Comparison of suspended sediment yield for the Lillooet River watershed (this study; red circle with error bars) and specific sediment yield (i.e. "the quantity of sediment passing a monitored river cross-section per unit area drained upstream of that section"; Church and Slaymaker, 1989, p. 452) in British Columbia. Closed symbols are data from natural landscapes; open symbols are data from landscapes influenced by natural or human disturbances. Measurements for Lillooet Lake are derived from a 57-year record of lake sedimentation reported by Gilbert (1973). Modified from Church and Slaymaker (1989).

Figure 11. Summary diagram comparing sediment yield in the Lillooet River watershed (bottom), dated landslides at Mount Meager (Friele et al., 2008), and glacier fluctuations in western Canada (top; modified from Clague et al., 2009) and Garibaldi Provincial Park (middle; modified from Koch et al., 2007). Horizontal bars show uncertainties in the ages of prehistoric landslides.

Figure 12. (a) AD 1931 and (b) 1776 varves from Lillooet Lake cores C, 2, and E (left to right; proximal to distal core locations). The vertical black bar at lower left of each photograph is 1 cm.

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667 Figure 13. Sediment yield and maximum daily discharge of Lillooet River during the twentieth century.

Draft

Article Map

Long-term sediment yield

Draft

Sediment yield post AD 1629

Recurrence intervals

Cumulative departure 1629-19987

Cumulative departures

Cumulative departures Q10

Persistence post 1629

Persistence 20th century

sediment yield vs. drainage basin

Sediment yield and glacial history

Varve pictures

Sediment yield 20th century