# Extreme sediment delivery events recorded in the contemporary sediment record of a montane lake, southern Coast Mountains, British Columbia

**Erik Schiefer, Brian Menounos, and Olav Slaymaker**

**Abstract:** The extreme sediment delivery regime of a montane catchment was examined through the analysis of recent lacustrine varve deposits recovered from a high-density sampling program. Years of anomalously high sediment yield from the Green Lake watershed were identified over a 70-year period (1930–2000) based on whole-lake varve deposit volumes. Intra-annual sediment delivery events were categorized and described for those anomalous years using historical hydroclimatic data and the stratigraphic record observed within inflow proximal sediment cores. Extreme sediment delivery coincided with high discharge conditions and elevated sediment availability resulting from (1) rapid glacier recession of the early twentieth century, (2) late-summer and autumn rainstorm-generated floods, and (3) freshet floods caused by unusual snowmelt conditions. The thickness and physical characteristics of varves vary among years that experienced different types of moderate and extreme sediment delivery events in relation to the defined average-regime depositional model. Several hydroclimatic factors can interact to produce composite varve units of anomalous thickness. In some cases, geomorphic events, such as landslides and channel changes, contributed to extreme sediment delivery in the Green Lake catchment. The interaction of these geomorphic effects, coupled with the variable nature of associated hydroclimatic functions, complicate paleoenvironmental assessments based on the lacustrine varve record.

**Résumé :** Le débit extrême de sédiments dans une zone de captage en montagne a été étudié par l'analyse des dépôts récents de varves lacustres prélevées dans le cadre d'un programme d'échantillonnage à haute densité. Des années de rendement anormalement élevé de sédiments en provenance du bassin versant du lac Green ont été identifiées sur une période de 70 ans (1930 – 2000) en se basant sur les volumes de varves déposés dans tout le lac. Les événements intra-annuels de livraison des sédiments ont été classés en catégories et décrits pour ces années anomales en utilisant des données historiques hydroclimatiques et les données stratigraphiques enregistrées ont été observées à l'intérieur des carottes de sédiments d'arrivée proximale. L'apport extrême de sédiments coïncide avec des conditions de grande décharge et de disponibilité élevée de sédiments résultant de : (1) une récession glaciaire rapide au début du 20$^{e}$ siècle, (2) des crues générées par des tempêtes pluviales tard dans l'été et à l'automne et (3) des crues causées par des conditions inhabituelles de fonte des neiges. L'épaisseur et les caractéristiques physiques des varves varient selon les années qui ont subi différents types d'événements de livraison, extrêmes et modérés, par rapport au modèle de déposition défini pour un débit moyen. Plusieurs facteurs hydroclimatiques peuvent interagir pour produire des unités composites de varves d'épaisseur anomale. Dans certains cas, des événements géomorphologiques, tels que des glissements de terrain et des variations de chenaux, contribuent à la l'apport des sédiments dans le bassin hydrologique du lac Green. L'interaction de ces effets géomorphologiques et la nature variable des fonctions hydroclimatiques compliquent les évaluations paléoenvironnementales basées sur les données provenant de varves lacustres.

[Traduit par la Rédaction]

## Introduction

Studies of glaciolacustrine deposits have advanced our understanding of the primary controls of sediment production, transport, and sediment yield in mountainous catchments (Wastegard et al. 1998; Hasholt et al. 2000; Slaymaker et al. 2003; Loso et al. 2004). Annually laminated (varved) sedimentary structures are common to these environments because sedimentation rates are typically high, bioturbation rates are low, and sediment transport to these

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basins is strongly seasonal (Smith and Ashley 1985). Analyses of glacial lake deposits often provide high-resolution records of past sedimentary environments and associated hydroclimatic variability. Consequently, a significant effort has been invested into using varved glaciolacustrine sequences as a paleoenvironmental proxy over a wide range of temporal scales (Gilbert et al. 1997; Lamoureux 2002; Menounos et al. 2005).

The most common and easiest attribute to measure in varve records is varve thickness. However, given the complexities of sediment production and transfers in mountain drainages, the interpretation of varve thickness trends from these watersheds is less than straightforward (Leonard 1997). Desloges and Gilbert (1994) proposed the following classification scheme for clastic varves:

(1) Average regime: departures in varve thickness associated with "normal" hydroclimatic fluctuations that exhibit limited variance about some stationary or gradually varying mean;
(2) Extreme regime: departures in varve thickness associated with "extreme" forcing events that fall beyond average regime variability; and
(3) Local events: discontinuous deposits that are only locally significant in the sediment record.

Using glacier-fed lakes of the southern Canadian Cordillera, Desloges and Gilbert (1994) suggested that long-term trends of sediment delivery are dominated by changes in the average state rather than extreme events. Nevertheless, an analysis of thick varves is of interest because these may be associated with important hydrological and geomorphic events, such as floods, landslides, or substantial glacial fluctuations, that present hazards for humans and infrastructure in mountain environments. This paper presents event- to annual-scale stratigraphic evidence of extreme sedimentation events in the sediment record of Green Lake over a 70-year period (1930–2000). The lake basin, which is situated in a developed mountain corridor of British Columbia, is known to contain notably well preserved varve deposits (Schiefer 2006*a*). Regional streamflow data (1930–2000), local meteorological records (1950–2000), and sequential aerial photography (1947–1999) allow us to assess the relation between extreme sedimentation and associated hydroclimatic and geomorphic controls.

The relation between lake sedimentation and hydroclimatic events has been assessed in an earlier study, but only for a small region of the lake where sediments are delivered primarily by overflow and shallow interflow events (Menounos 2006). Underflow is an important process that is known to deliver exceptional quantities of sediments to montane lakes during floods (Gilbert 1975; Gilbert et al. 1997; Best et al. 2005). Consequently, the present study considers those extreme events where sediments were probably distributed in Green Lake by a combination of interflow, overflow, and underflow processes.

## Study area and methods

The Green Lake catchment drains 174 km$^2$ of the southern Coast Mountains of British Columbia (Fig. 1). Major sediment sources to the lake include glaciers (7% of watershed area), glacier forefields, landslides, and reworked Pleistocene valley fill. Bedrock geology is typical of the Coast Plutonic Complex, consisting of granodiorite to quartz diorite intrusions and minor pendants of volcanic and sedimentary terrain (Monger and Journeay 1994). Human development has been primarily restricted to the lower valley area, where the resort municipality of Whistler is now situated. Historical land use activities in the region are documented by Petersen et al. (1985). Early developments involved railway construction in 1911 followed by small-scale logging and sawmill operations up to 1956. More recent and intensive land use activities included timber harvesting during the 1960s and 1970s (~10% of catchment logged), followed by resort development that has continued to the current day (~2% of catchment urbanized).

Green Lake is a small (2.0 km$^2$), moderately deep (44 m), montane lake formed by Pleistocene glacial erosion along a fault-controlled valley bottom (Fig. 1). Major inflows to the lake include Fitzsimmons Creek, River of Golden Dreams, and Nineteen Mile Creek. Distinctive rhythmic sequences recovered from the lake have been interpreted as varves based on the following lines of independent evidence:

(1) The stratigraphic detail of the Green Lake couplets are similar to clastic varve deposits that have been described in other proglacial lakes of the southern Coast Mountains (Desloges and Gilbert 1994; Slaymaker and Menounos 2000; Menounos et al. 2005). Repeated core recovery over a four-year period confirm recent deposition of annual couplets (Menounos 2002; Schiefer 2004).
(2) The Green Lake varve counts fall within bracketing dates obtained from independent radiometric dating using two radionuclides, including residual $^{137}Cs$ from thermonuclear fallout and natural $^{14}C$ decay within recovered organics (Menounos et al. 2006).
(3) Two different anthropogenic markers are observed in sediment cores obtained from sites near the south shore of Green Lake, including blast rock fragments and sawdust debris. These markers relate to nearshore railway construction and historical sawmill operations, respectively (Schiefer 2006*a*).

Meteorological records, obtained from stations at 685 m and 1840 m above sea level in the study catchment, showed that the local temperate–maritime climate is subject to strong altitudinal gradients in temperature and precipitation. Discontinuous stream discharge records were available for the Green Lake outflow (1930–1947) and the Fitzsimmons Creek inflow (1994–2002). We primarily utilized a high quality streamflow record from nearby Lillooet River (1930–2002), situated 20 km to the northeast, as a proxy for Green Lake runoff conditions. All hydrographic records are characterized by low flows during the winter, high freshet discharges in the late spring and early summer, and infrequent rainstorm-generated floods during the autumn. Despite the large difference in watershed areas (Lillooet catchment area = 2150 km$^2$), discharge patterns between the Fitzsimmons and Lillooet basins are similar (Fig. 2). We used the Spearman rank order statistic to assess correlations between the two daily mean discharge series due of the highly skewed nature of the discharge data and because a near-

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**Fig. 1.** Catchment area map and Green Lake bathymetry showing the locations of the three primary coring sites and the lake-wide sampling grid.

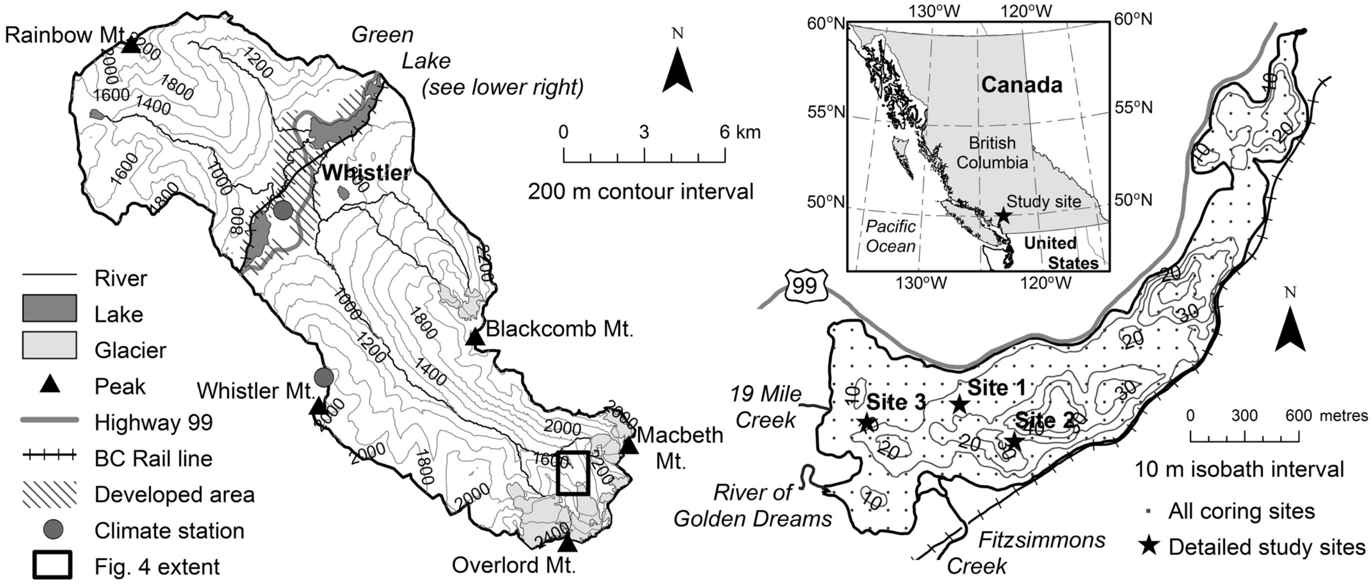
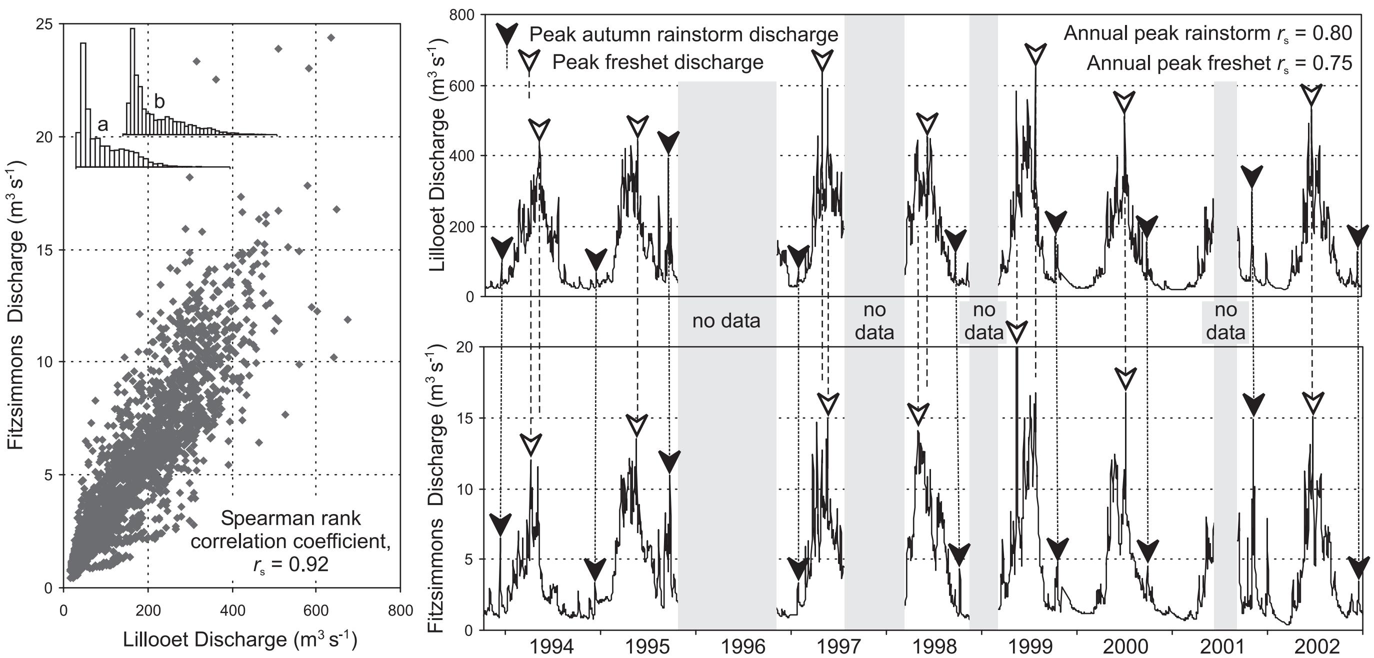



**Fig. 2.** Scatter plot and inter-annual hydrographical comparison of the mean daily discharge time series for Lillooet River and Fitzsimmons Creek. Inset bar graphs on scatter plot show histograms of the plotted Lillooet River (*a*) and Fitzsimmons Creek (*b*) hydrometric data. Annual peak freshet (June–August) and autumn rainstorm (September–November) discharge events are marked by open and closed arrowhead symbols, respectively. Dashed and dotted vertical lines extended from freshet and rainstorm flood markers aid the comparison of event timing between hydrometric records. Spearman rank order coefficients are included as measures of the linear correlation between the full discharge series ($n$ = 3272) and the individual annual peak freshet ($n$ = 7) and autumn rainstorm ($n$ = 9) discharge events for the two streamflow records. Shaded areas indicate gaps in the hydrometric records.




linear relation was observed between the records. The records are strongly correlated ($r_s$ = 0.92, $p$ < 0.001), which reflects the broadly similar seasonal variations between these highly autocorrelated series. The records are also correlated for the peak annual autumn flood (September to November: $r_s$ = 0.80, $p$ < 0.05) and for the annual freshet flood (June to August: $r_s$ = 0.75, $p$ < 0.05) (Fig. 2). Peak autumn floods occur within two days of each other for the Fitzsimmons Creek and Lillooet River basins, suggesting that the high flows are caused by similar meterological conditions. In contrast, the timing of snowmelt-driven floods varies substantially between the basins from a few days (e.g., 1995,

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2000, 2002) to over two months for the unusual snowmelt year of 1999. Similar correlations also characterize the relation between daily discharge from the outlet of Green Lake and Lillooet River during the period 1930–1947.

We used a 100 m grid sampling scheme to reveal sedimentation patterns at 202 evenly distributed sampling sites in the lake (Fig. 1). We chose this dense sampling scheme to calculate whole-lake sedimentation rates given the relatively complex bathymetry of Green Lake. Sediment cores up to 1 m in length were recovered using a 7.6 cm diameter Kajak-Brinkhurst gravity sampler (Glew et al. 2001). Cores were split lengthwise and repeatedly photographed while drying to reveal faint sediment structures only visible in a partially dried state (Gilbert 1975). The cores were subsampled every 2.5 cm using a 1 $cm^3$ syringe and analyzed for bulk physical properties (Håkanson and Jansson 1983). A detailed description and analysis of the bulk physical properties of the Green Lake sediments is provided by Schiefer (2006*b*). Thickness measurements of laminae (±0.1 mm) were made from digital imagery of the freshly split cores.

For a given year and sampling site, the annual sedimentation rate (g $cm^{-2}$ $a^{-1}$) was calculated as the product of the corresponding varve thickness (cm $a^{-1}$) and the mean dry sediment density (g $cm^{-3}$) for the site. Minimal compaction effects were observed in the core records. Annual lake sediment deposition (Mg $a^{-1}$) was estimated by multiplying the averaged lake-wide sedimentation rate for the year by the total lake area. Varve chronologies range from decades near the Fitzsimmons Creek inflow and in the deepest sites of the proximal basin to centuries in the distal basins. Varve sequences were disrupted in a small number of cores (<10) owing to post-depositional bioturbation at shallow sites (<2 m) or subaqueous slope movements on some steep bottom slopes (>15°). To complete sediment flux records at sites where a continuous contemporary chronology could not be established, incomplete varve series were extended by cross-correlation with adjacent cores (Schiefer 2006*c*). This technique was deemed more appropriate than increasing the contributing areas for cores with a complete chronology because observed spatial variability of varve thicknesses exceeded the resolved temporal variability in the lacustrine deposits. Errors were estimated as the root mean square of laboratory precision limits for stratigraphic and density measurements.

## Contemporary varve record

We developed a 70-year (1930–2000) record of average varve thicknesses for Green Lake and identified annual deposits characteristic of the extreme regime from this contemporary chronology (Fig. 3). Varves deposited after 2000 were not measured for analysis owing to the frequent disturbance of the topmost portion of the cores during recovery and processing. The 1930 varve was selected as a lower age bracket for this study because of the availability of high-quality stream discharge records from that time in the region. The 1930 couplet was also relatively easy to recognize in the sediment record, and the 70-year chronology could be recovered over most of the lake basin by gravity coring techniques. Analysis of the longer term sedimentary record (>100 years), which was developed from long (>1 m) sediment cores recovered from Green Lake about 200 m east of site 1 (Fig. 1), indicated greater inter-annual variability in sediment delivery during recent decades (Menounos et al. 2005; Menounos 2006). Although there is a high degree of within-lake spatial variability in varve thicknesses, twentieth century varve records are highly correlated throughout the Green Lake basin. Detailed within-lake patterns of sedimentation are described by Schiefer (2006*c*). With the exception of a few sites directly impacted by nearshore railway construction and sawmill operations (Schiefer 2006*a*), sedimentation rates were generally low during the periods of most intensive land use activities, including logging during the 1960s to mid-1970s and significant resort expansion during the 1980s. Most land use also occurred in low relief areas that are decoupled from contemporary streams. Variability in lake-wide sediment delivery is, therefore, interpreted to primarily reflect natural hydroclimatic and geomorphic watershed processes.

Most anomalously thick varves in the Green Lake contemporary record exhibit multiple graded laminae reflecting distinct episodes of intra-annual sediment delivery. Varves with an average thickness >0.80 cm (1.5 standard deviations above the contemporary record median) are considered to represent extreme-regime sedimentation events for this study (Fig. 3). Preliminary work indicates that the high sedimentation rates observed during those years can be linked to three hydroclimatic conditions, including (1) episodes of rapid glacier recession, (2) rainfall-generated floods during late summer and autumn, and (3) unusual snowmelt conditions during the late spring and summer (Schiefer 2004; Menounos 2006). Cores recovered from sites of moderate depth at the inflow proximal side of the lake exhibit the best-preserved signatures of these major sediment delivery events. Unconformities disrupt the record at deep sites of the proximal basin, and there is a non-linear decrease in varve thicknesses in more shallow and distal lake settings. For these reasons, the reconstruction and interpretation of intra-annual sediment delivery events are restricted to three undisturbed cores recovered from inflow-proximal sites situated on lake bottom sills (Fig. 1). The characteristics of extreme-regime varve deposits and associated hydroclimatic and geomorphic conditions are examined in the following sections. Subsections are included for describing individual extreme events, as well a few other identified events of interest.

## Extreme sediment delivery events

### Rapid glacier recession

Although local meteorological records are limited for the 1930s and early 1940s, regional assessments of the available instrumental record suggest that anomalously warm and dry conditions prevailed in the southern Coast Mountains during this period (Menounos 2002). Aerial photographs show that glaciers retreated rapidly over this period and, in the case of the Green Lake basin, some glacier forefields approximately doubled in size (Fig. 4).

The 1930–1945 sedimentary record is notable in Green Lake as a sequence of well-defined varves of above average thickness, including half of the identified extreme-regime deposits. The average sedimentation rate for 1930–1945 ex-

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**Fig. 3.** Average Green Lake varve thicknesses for the contemporary period. Error bars are based on root mean square measurement errors. Symbols mark major sediment delivery years with a varve thickness exceeding 0.80 cm.

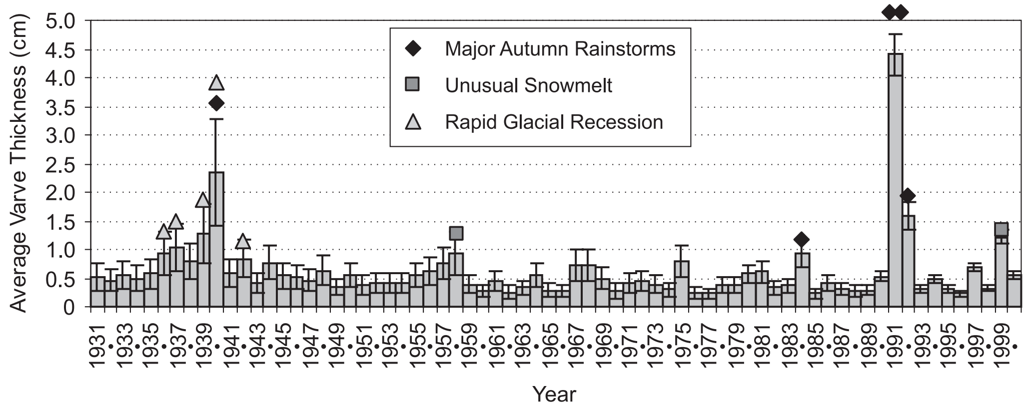
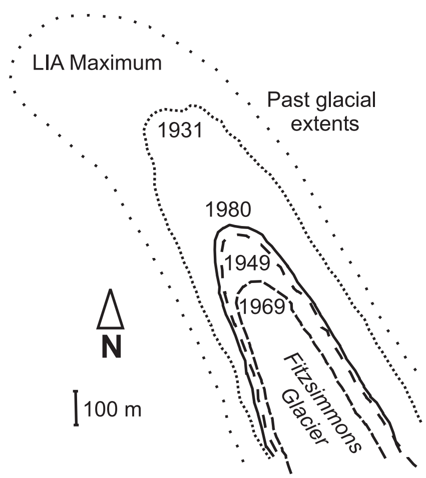



**Fig. 4.** Fitzsimmons Glacier frontal retreat from the Little Ice Age (LIA) maximum based on outermost moraine positions and sequential aerial photographs (after Menounos 2002).




ceeds the average rate for the remainder of the twentieth century by about 30%. These thick varves are distinctive and consist of light gray silt beds overlain by dark clay caps (Fig. 5). The silts are interpreted to reflect high-energy, open-water sediment delivery processes, whereas the clays were probably deposited in the lake under ice cover. Varves deposited prior to 1930 and after 1945 are thinner, less distinct, and more commonly bioturbated.

Elevated suspended delivery from 1930 to 1945 is attributed to increased sediment supply associated with rapid glacier recession. Sediment production from glacial sources tends to be greatest during periods of rapid fluctuations in ice extent (Leonard 1997). Elevated sediment yields may also reflect a paraglacial effect (Ballantyne 2002) because fresh glaciogenic material is mobilized into proglacial stream networks. Sediment core subsamples collected within the rapid glacier recession period exhibit slightly lower organic contents and a higher sediment density, typically exceeding sampling site averages by about 5%. Limited particle size data show the sediment to be finer than the overlying contemporary sediments. Average annual lacustrine sediment deposition for the period 1930–1945 is 15 500 Mg $a^{-1}$.

The thickest and most distinct varves of the rapid glacier recession period were deposited between 1936 and 1944 (Fig. 5). The thickest couplet in the sequence is the 1940 varve, which includes a major autumn rainstorm deposit (discussed in the next section). The 1937, 1938, 1942, and 1944 multiple-component varves coincide with the occurrence of moderate autumn rainstorm events. The microlaminated appearance of the upper portion of the 1944 varve correlates well with the numerous autumn flood events for that year. Late autumn floods do not appear as subannual laminae in the varves of 1939 and 1941, a trend that is consistent with other notably late autumn rainstorms of the contemporary period (discussed in the following section). The thinnest varve of the sequence was deposited in 1943, the year with the lowest magnitude snowmelt flood for that period and no significant autumn rainstorm events. The total amount of lacustrine sediment deposited in Green Lake during 1936–1944 (excluding 1940) varies between 8 000 ± 3 400 Mg for 1943 and 19 700 ± 8 300 Mg for 1937.

## Major autumn and summer rainstorms

### *1940 autumn rainstorm*

In mid-October of 1940, a major autumn rainstorm flood occurred in the Whistler region (Table 1). There is no temperature data available for the Whistler area; however, it is likely that a large proportion of the catchment area received precipitation as rain during the storm. Unvegetated debris flow channels are observed in 1947 aerial photographs of the catchment, and it is likely that many were active sediment sources during this and other autumn storm events of the early contemporary period.

The 1940 varve consists of a thinner lower unit, interpreted to represent sediment delivery during the freshet, and a thicker upper unit, likely associated with the extreme autumn rainstorm event (Fig. 5). Hysteresis in fluvial sediment transport may explain the rapid up-core transition to coarse sediments in the lower freshet deposit, which are overlain by a more gradual normally graded bed, despite the near symmetric nature of the snowmelt flood for that year. The thicker upper component of the 1940 varve is interpreted as the major autumn rainstorm event deposit. This component consists of coarser silt sediments with several smaller scale laminated structures of varying distinctiveness. The cause of these intra-event sedimentary structures is unknown. They may be related to short-term fluctuations of flood flows or

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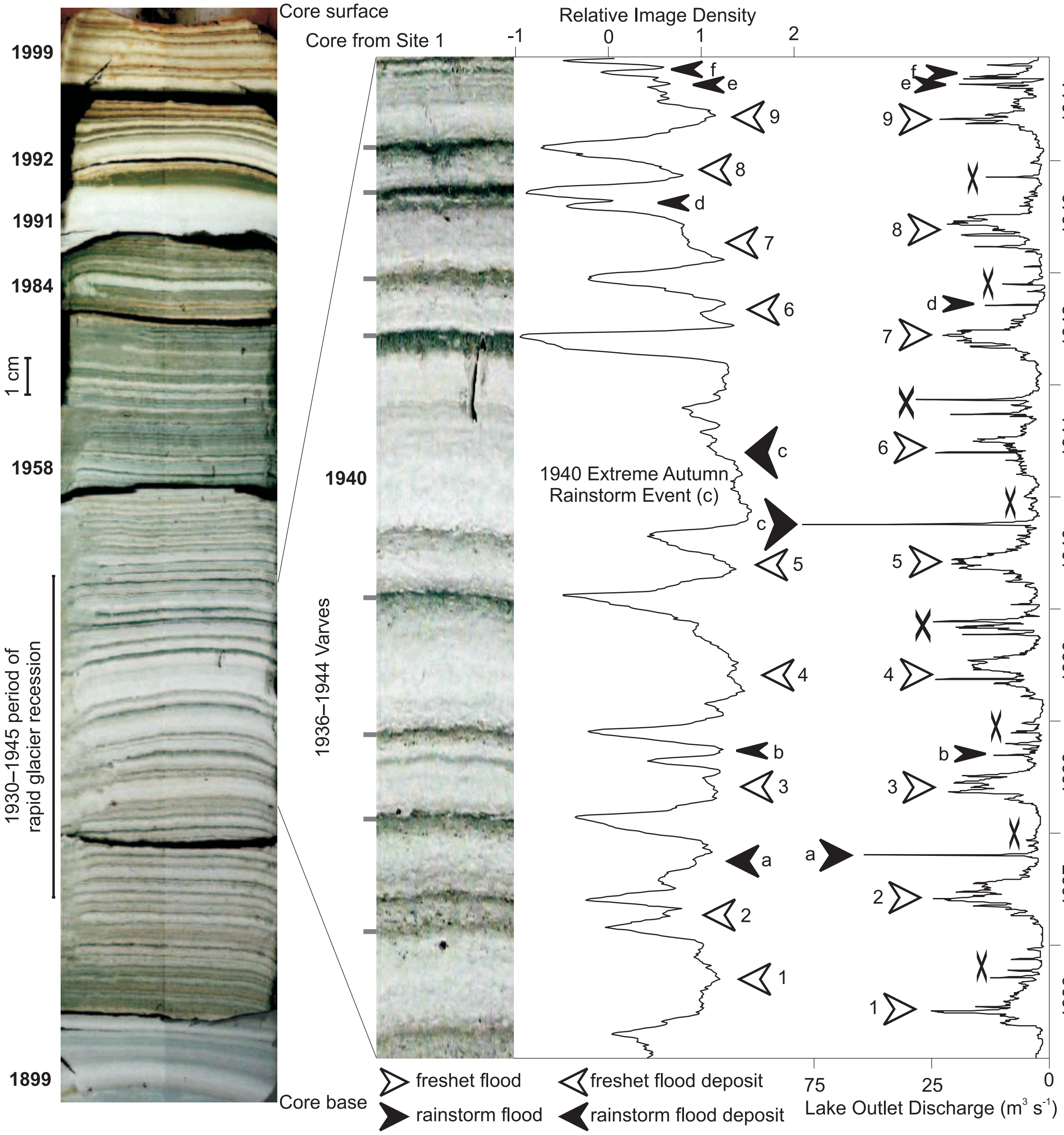
**Fig. 5.** Sediment core composite image for site 1 with detail of the 1936–1944 varve sequence. Image density is presented as a relative scale in standard deviations from the mean image density. Arrowhead symbols mark inferred corresponding peaks of coarser sediment (lighter tone) and high discharge events, distinguished by summer freshet (hollow symbols) and autumn rainstorm floods (filled symbols). Uncorrelated late autumn and winter high-discharge events are marked with an "X".




inflow circulation patterns during the event. A relatively thick and well-defined clay cap overlies the storm deposits and completes the 1940 sedimentary unit. The thickness of the 1940 varve may also be associated with elevated sediment mobilization from glacial sources because the flood event occurred during the period of rapid glacier recession. This is an example in which an autumn rainstorm event of high magnitude and low duration has dominated annual lake sediment delivery.

### *1984 autumn rainstorm*

In early October 1984, another major rainstorm-generated flood occurred in the region (Table 1). Temperature records indicate that almost all of the catchment area likely received precipitation as rain during the storm peak. A high proportion of debris flow channels in the surrounding region were observed to be active during this event (Jordan and Slaymaker 1991).

The 1984 composite varve is one of the most clearly distinguished and broadly distributed varves within the contemporary Green Lake sediments. Sediment cores recovered from site 2 reveal the fine-scale sedimentary structure associated with this varve and other recent extreme-regime deposits (Fig. 6). The lower lamina (a in Fig. 6) is interpreted to be associated with the snowmelt freshet flood for 1984. It is a relatively thin freshet deposit for the contemporary pe-

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**Table 1.** Hydroclimatic and sedimentological characteristics of major catchment rainstorm events.

| | 1940 | 1984 | 1991 | 1992 |
|---|---|---|---|---|
| Daily mean flood discharge[a] | 900 $m^3$ $s^{-1}$ (18 Oct)<br>rank = 3 | 1110 $m^3$ $s^{-1}$ (7 Oct)<br>rank = 2 | 1260 $m^3$ $s^{-1}$ (30 Aug)<br>rank = 1 | 808 $m^3$ $s^{-1}$ (23 Oct)<br>rank = 5 |
| Valley precipitation 1-day/5-day[b] | 57.9 mm<br>85.8 mm | 60.7 mm<br>82.5 mm | 64.4 mm<br>155.7 mm | 36.2 mm<br>127.4 mm |
| Valley temperature 1-day/5-day[b] mean | na<br>na | 10.7 °C<br>9.9 °C | 11.5 °C<br>10.8 °C | 10.0 °C<br>8.5 °C |
| Alpine temperature 1-day/5-day[b] mean | na<br>na | 5.0 °C<br>3.7 °C | 5.0 °C<br>4.0 °C | na<br>na |
| Other hydro-geomorphic factors | Coincident with rapid glacier recession | | Antecedent rainfall and major landslide | Channel adjustments |
| Total annual sediment delivery | 42 800±18 400 M<br>rank = 2 | 17 100±4 800 Mg<br>rank = 8 | 78 000±7 200 Mg<br>rank = 1 | 29 400±4 900 Mg<br>rank = 3 |
| Flood deposit:varve thickness ratio | 0.75 | 0.83 | 0.91 | 0.52 |
| Other depositional features | Microlaminated | Sand lenses | Coarse sands with thick graded beds | Microlaminated |

**Note:** na, not applicable.
[a]Rank based on late summer and autumn rainstorm-generated flood discharges for the Lillooet River (1930–2000).
[b]5-day values include day of flood and preceding four days.

riod, likely a reflection of the low-magnitude snowmelt flood for that year (388 $m^3$ $s^{-1}$). The overlying bed (b in Fig. 6) is attributed to the major autumn rainstorm of that year. It is a thicker unit that grades from fine sand to a well-defined winter clay cap. The graded bed is interrupted by sand lenses of varying thicknesses, which may relate to inflow turbidity current pulses or sediment slump failures along the delta front during the event. These lenses are sparse in the lower portion of the event deposit, abundant in the middle portion, and are not observed in the upper portion of the bed. The increased deposition of sand lenses midway through the deposit may indicate the exceedance of a geomorphic threshold during the flood that increased the occurrence of energetic density flow events. The termination of the sand lenses occurs where the graded bed enters the silt-size fractions and likely indicates the transition to sediment deposition by settling through the water column following flood discharges. This is another example of when a high-magnitude, low-duration autumn rainstorm event dominated annual sediment deposition in the Green Lake basin.

### *1991 late summer rainstorm*

In late August of 1991, an extreme rainstorm flood was observed in the Whistler area (Table 1). This produced the record flood for many gauged watersheds in the southern Coast Mountains and exceptionally thick varves in other nearby proglacial lakes (Menounos et al. 2005). The storm was the result of a major low-pressure system that stalled off the west coast of the province, a condition more typical of winter months. There was no alpine snowpack because of the earlier timing of this event, resulting in less runoff attenuation by snow cover. Valley and alpine temperatures were also warmer than similar autumn events, resulting in rainfall at all elevations for the entire storm cycle. Rainfall-return period analysis carried out by Ward and Skermer (1992) demonstrates the rare nature of this extreme event, particularly when seasonal timing is considered (Table 2). High base flows at the time also contributed to the severe runoff because of the unusually wet weather of the preceding month. A storm earlier in August produced a Lillooet River flood discharge of 893 $m^3$ $s^{-1}$.

In addition to a large number of storm-triggered debris flows, the event reactivated a major deep-seated failure in Quaternary valley-fill sediments, involving up to 1 000 000 $m^3$ of material, about 3 km upstream of Green Lake in the lower Fitzsimmons Creek valley (Mierzejewski et al. 1993). Evidence of a temporary landslide dam up to 6 m in height was observed at the site, including fine-grained deposits upstream, an abandoned channel on the bank opposite the landslide, and extensive vegetation damage downstream. It is possible that instantaneous stream discharges following the breaching of the landslide dam exceeded all other contemporary flows of Fitzsimmons Creek. Vertical change in the channel, following initial aggradation and later scour, exceeded 5 m at several locations (Ward and Skermer 1992).

The 1991 varve consists of several distinct graded beds (Fig. 6). The lowest bed unit (c in Fig. 6) is interpreted to be associated with the snowmelt freshet. Fine-grained sediments overlying the freshet deposit are interrupted by a similar, slightly thicker graded bed (d in Fig. 6) that is believed to be associated with the early August rainstorm flood that year. Another layer of fine-grained sediments was deposited during the falling limb of the freshet and truncated by the extreme late August rainstorm event bed (e in Fig. 6). This event deposit is the thickest and most easily recognized marker bed in the suite of sediment cores recovered from Green Lake. The lowermost component of the flood deposit consists of a coarse-grained layer that is dominantly sand in the delta proximal region of the lake. The deposit fines upward and contains intercalated sand lenses that may record turbidity currents. Coarsest sands are observed midway

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**Fig. 6.** Lillooet River hydrographs and rainstorm data for 1984, 1991, and 1992. Maximum daily discharges (Qmax) are given for the dominant rainstorm-generated floods. Corresponding varve deposits from site 2 are shown with inferred event-based correlations denoted by letter symbols a to h (see text).

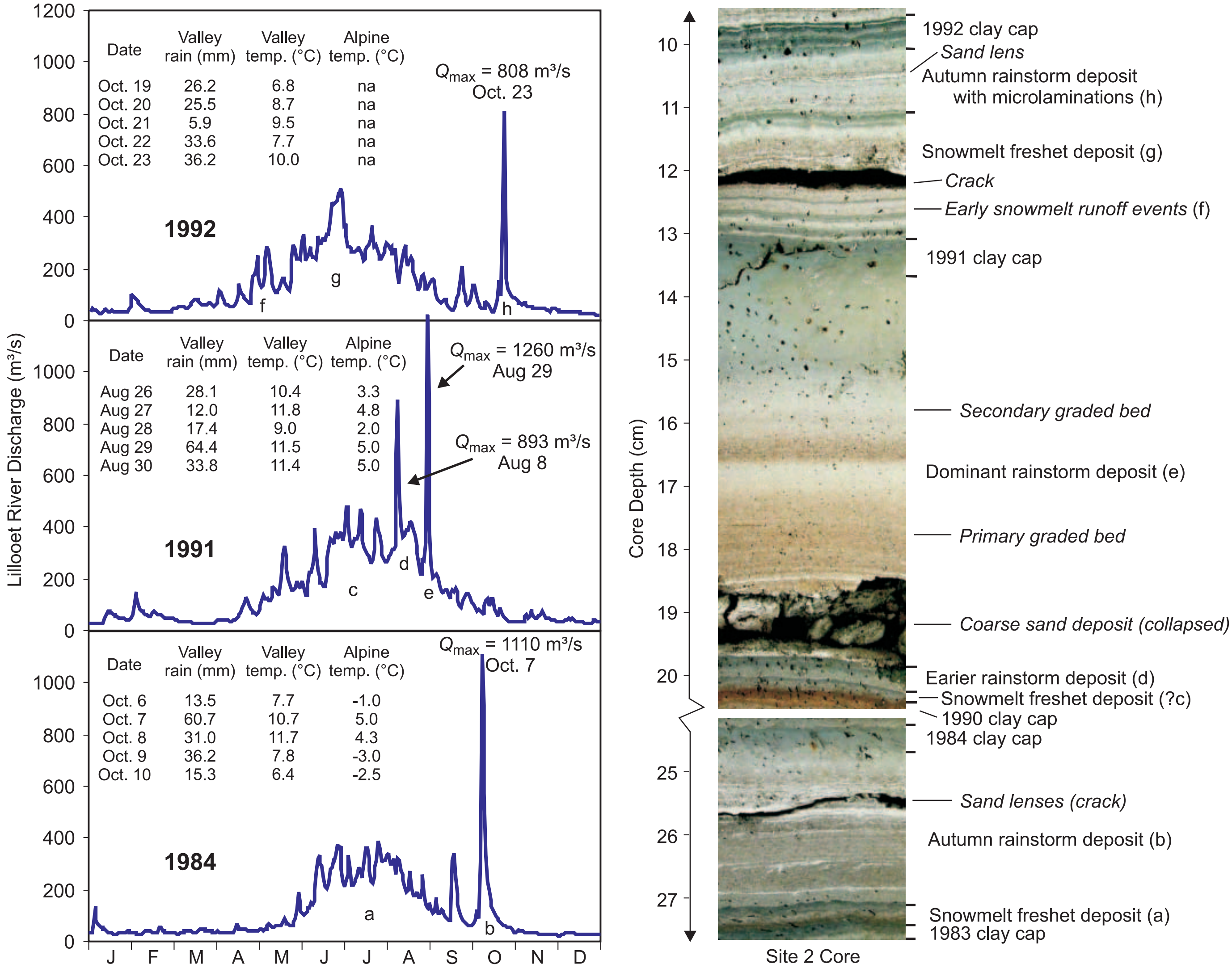


**Table 2.** Rainfall return period analyses for the 30 August 1991 rainstorm (after Ward and Skermer 1992).

| Period analyzed | Return period (24-hour rainfall) | Return period (monthly rainfall) |
|---|---|---|
| Annual | 8.8 years | 4.1 years |
| April–October | 19.5 years | 6.6 years |
| May–September | 97.4 years | ~190 years |

through the storm deposit. This may be associated with the failure of the Fitzsimmons Creek landslide dam or some other type of significant inflow adjustment or delta slump. Overlying the coarse grained sediment layers the deposit gradually grades into a thick winter clay cap.

### *1992 autumn rainstorm*

Another major rainstorm flood occurred in late October of 1992 (Table 1). Daily precipitation totals were lower during this event than during other rainfall-generated floods; however, persistent rain over a one-week period resulted in a moderately high five-day total accumulation. Temperatures were slightly cooler relative to other events, suggesting that a larger proportion of the catchment may have remained below the freezing level during the storm. Unfortunately no alpine temperature data are available for the year. At the time of this event, many river channels in the region were still responding to the extreme rainstorm floods of 1991 (Menounos 2002). Significant channel alterations caused by the 1991 flood along the lower valley of Fitzsimmons Creek are apparent in aerial photographs (Fig. 7). It is likely that unstable channel banks and bars, as well as fresh landslide scars and deposits, activated by the extreme 1991 storm, continued to be important sediment sources during the 1992 event.

The 1992 varve deposit contains one of the more complicated annual sequences observed within the Green Lake record (Fig. 6). The thick clay cap of 1991 is disrupted by several coarser laminations of increasing thicknesses up core (f in Fig. 6). These are attributed to periodic sediment trans-

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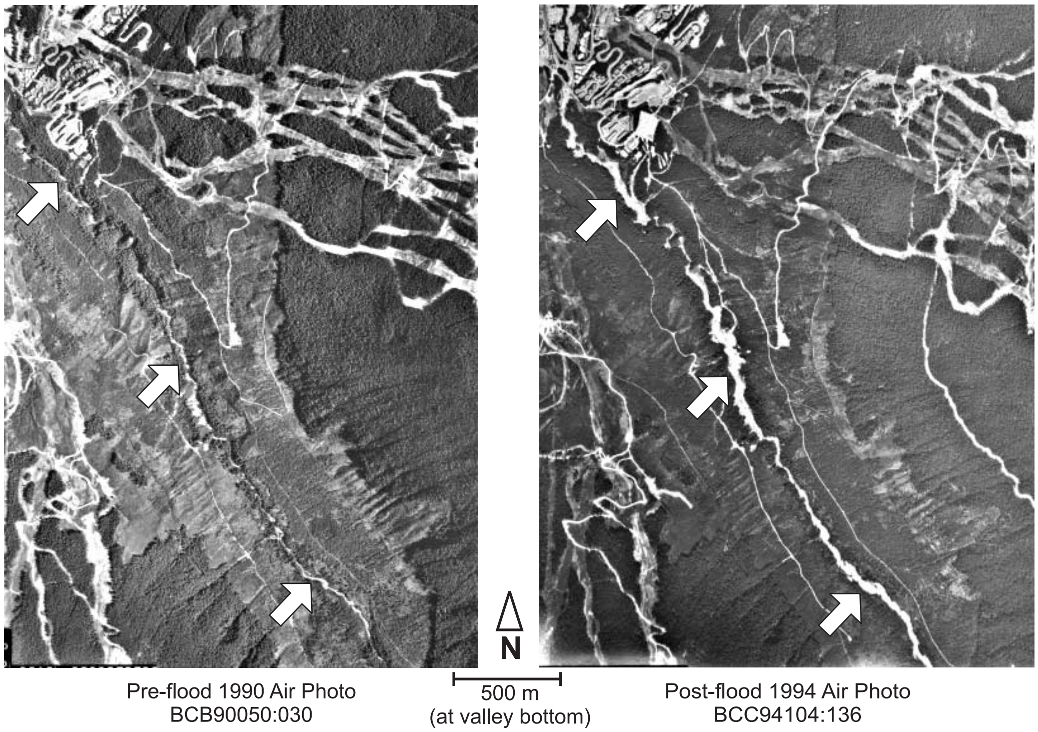
**Fig. 7.** Fitzsimmons Creek channel change following the 1991 major autumn rainstorm event. Fitzsimmons Creek runs from bottom right to top left in both photographs. Comparison points along the stream channel are marked with arrows. Other high-contrast image features include urban structures (top left), ski-resort trails (top right), and forest roads (bottom left). Photo scale is approximately 1 : 35 000 along the valley bottom.




fers during the ice-breakup period and early snowmelt-runoff events. The varve is composed of two thick graded beds that contain numerous smaller scale graded structures and fine sand lenses. The two graded beds are interpreted to reflect the snowmelt freshet (g in Fig. 6) and autumn rainstorm floods (h in Fig. 6) observed that year. Both of those event beds appear to be anomalously thick for the observed flood magnitudes. Many of the smaller scale vertical structures observed within the snowmelt flood event sequence weakly coincide with fluctuations in the stream discharge record. This relation with discharge is not observed for stratigraphic features within the autumn flood deposit, suggesting a more complex geomorphic response during the rainstorm event.

Unlike the previous signatures discussed, the 1992 rainstorm deposit is only marginally thicker than the underlying snowmelt deposit. There are a few distinct characteristics of the 1992 flood events that may explain the unusual relative thickness of the snowmelt freshet deposit during a year that experienced a major rainstorm event. Firstly, the freshet flood for the year (513 $m^3 s^{-1}$) was notably larger than those observed in 1940, 1984, and 1991. Secondly, the snowmelt freshet flood of 1992 was the first high-discharge event following the major channel disturbances caused by the extreme flood of 1991. It is probable that, following the period of low winter discharge, many of the disturbed channel reaches in the catchment were particularly unstable during the moderate 1992 freshet. Thirdly, the autumn rainstorm event of 1992 occurred late enough in the season that a significant proportion of the watershed likely remained below the freezing level during the storm, thus reducing the potential for sediment recruitment from alpine areas.

### *Other autumn rainstorm events*

Varves that coincide with other high flows during autumn reveal a complex relation to hydroclimatic events (Table 3). Varves deposited during those years are all of above average thickness, and all display sedimentary structures that indicate sedimentation by multiple inflow events. The 1999 varve is the thickest deposit of the set even though the year experienced the least intense rainstorm precipitation. Unusual snowmelt conditions may explain the high sediment delivery to Green Lake that year (discussed in the next section).

The timing of runoff events and air temperatures during these events appears to be as important as precipitation totals for other thick varves deposited during years of significant autumn flooding. Varves deposited during years that experienced earlier or warmer autumn rainstorms (1956, 1957, 1967, and 1975) are thicker than those associated with later or cooler rainstorms (1980, 1981, and 1990). The timing of runoff events and air temperatures probably controls the elevation of the snowline and, hence, the proportion of the catchment that receives rain rather than snow during the precipitation event. The rainstorm deposits for the years that experienced a late event typically appear more brown

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**Table 3.** Hydroclimatic characteristics of other autumn rainstorm flood events of the contemporary period.

| | | | Mean valley temperature (°C) | | Valley precipitation (mm) | | |
|---|---|---|---|---|---|---|---|
| Year | Date | Peak daily discharge ($m^3\ s^{-1}$)[a] | 1-day | 5-day[b] | 1-day | 5-day[b] | Annual sediment deposition (Mg)[c] |
| 1956 | 25 Sept | 564 (11) | 13.1 | 9.3 | 28 | 58 | 11 400±4 700 (19) |
| 1957 | 5 Sept | 716 (8) | 13.9 | 13.9 | 53 | 67 | 13 800±5 600 (14) |
| 1967 | 10 Oct | 527 (12) | na | na | 70 | 142 | 13 200±5 300 (16) |
| 1975 | 4 Nov | 782 (7) | 6.9 | 6.9 | 43 | 110 | 14 600±5 700 (11) |
| 1980 | 26 Dec | 790 (6) | 5.0 | 0.7 | 57 | 107 | 10 500±3 100 (22) |
| 1981 | 31 Oct | 823 (4) | 6.2 | 5.4 | 55 | 147 | 11 100±3 700 (20) |
| 1990 | 11 Nov | 591 (10) | 4.6 | 1.9 | 72 | 163 | 9 800±2 000 (30) |
| 1999 | 24 Aug | 649 (9) | 14.9 | 17.2 | 23 | 23 | 22 500±2 600 (5) |

[a]Rainstorm-generated flood rank in parentheses (1930–2000) for Lillooet River.
[b]Includes day of flood and preceding four days.
[c]Total varve thickness rank in parentheses (1930–2000).

(10YR6/6 to 10YR3/3) than those deposited by early autumn floods, which are varying shades of gray (10YR7/1 to 10YR3/1). This may reflect higher organic contents of late-season deposits because sediment source areas will be increasingly dominated by forested valley bottom regions during those low-elevation floods. Considerable autumn leaf-fall debris and tannin compounds would also be available for entrainment from vegetated terrain during late-season events.

The latest date of a major rainstorm flood for the Lillooet River was 26 December 1980. At the Whistler valley bottom, over 16 cm of snow on the ground melted during the storm. In the alpine areas, the snow base decreased from 116 to 105 cm during the event that delivered mixed precipitation with alpine temperatures remaining near 0 °C. At sediment coring site 3, proximal to the Nineteen Mile Creek inflow, the 1980 rainstorm deposit is the thickest of all event signatures observed (Fig. 8). The locally thick 1980 unit is interpreted to reflect a greater hydrological response of the smaller and lower elevation Nineteen Mile Creek watershed to the late-season event. Organic content of sediment subsamples taken within the 1980 varve range from 7% to 11%, well above the site average of 4%. Distinctive colouring, especially the relative "redness" of the sediments, discriminates notably late rainstorm deposits and other organic-rich beds from the sediment record (Fig. 8).

Not all major rainstorms produce floods or elevate sediment delivery to the Green Lake basin. This has included the top three daily rainfall events recorded in the Whistler valley (75.4 mm, 1 December 1941; 78.0 mm, 24 October 1955; 79.2 mm, 7 January 1983). Many of the heaviest rainfalls recorded in the valley occur during the winter when significant snow cover and low temperatures effectively attenuate surface runoff resulting in no significant flood discharges or unusual sediment deposition in the lake basin (e.g., December 1941 and January 1983). High antecedent base flows and soil saturation were associated with the severity of the 1991 autumn rainstorm event. Conversely, unusually dry antecedent conditions may reduce the flood intensity of a short-lasting, heavy rainfall event (e.g., October 1955).

## Unusual snowmelt conditions

### *1958 snowmelt season*

Climate data for the Whistler valley show that May to August, 1958 was one of the hottest and driest four-month periods on record. Consequently, stream discharge remained well above average for most of that summer (Fig. 9). Above average precipitation was recorded through the 1957–1958 autumn and winter seasons. Mean temperatures during the winter were also above average, but remained low enough that a considerable snow base likely accumulated for most of the catchment. On 26 May 1958, following several hot days of near-record monthly temperatures, the Lillooet River reached its peak daily snowmelt discharge for the year (549 $m^3\ s^{-1}$). Following another hot period, a second large snowmelt flood of similar magnitude occurred on 17 June 1958 and discharge continued to be above average for the remainder of the snowmelt period. The unusually hot summer of 1958 likely resulted in a significant degree of alpine snowfield ablation and glacier melt. This melting may have increased the extent of high-elevation sediment source areas during the late summer. Two moderate autumn rainstorm floods (445 $m^3\ s^{-1}$ and 345 $m^3\ s^{-1}$) were also observed in the hydrological record for the year. The total annual discharge volume for 1958 is greater than any other year in the Lillooet River record.

The 1958 varve consists of a series of graded beds of varying thicknesses (Fig. 9). The lowermost bed, which is the thickest component of the 1958 varve, is interpreted to be associated with the initial snowmelt flood of late May when the highest discharges for the year were observed. The remainder of the varve consists of three additional graded beds. The upper two are likely associated with the moderate rainstorm flood events of that year. The other intermediate bed may be related to a minor flood peak that occurred late during the snowmelt freshet. On average, the freshet flood signature accounts for 66% of the 1958 sedimentary unit. This is an example in which a long duration snowmelt flood of moderate magnitude has dominated annual lake deposi-

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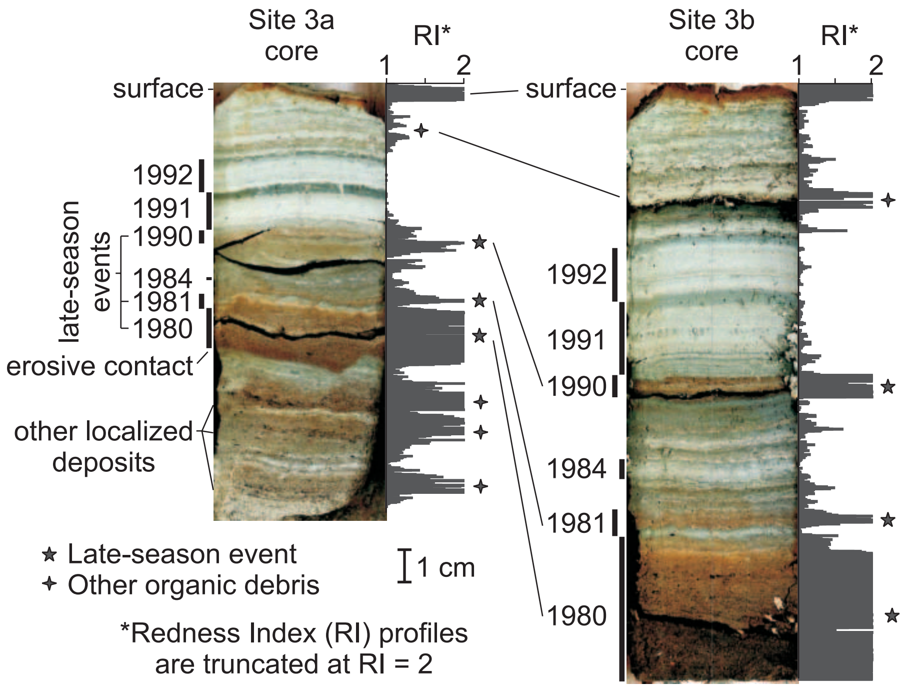
**Fig. 8.** Composite sediment core images and redness index (RI) profiles for two adjacent cores obtained near site 3. RI is the ratio of red channel intensity to the mean of green and blue channel intensities from the colour core imagery. Major late-season rainstorm deposits are characterized by high RI values (RI > 2) and are correlated between cores. Sediments at the sediment–water interface and localized organic debris-rich deposits also exhibit high RI values.




tion despite the occurrence of two rainstorm events that year. The total amount of lacustrine sediment deposited in Green Lake in 1958 is calculated to be 17 300 ± 7 400 Mg.

### *1999 snowmelt season*

The 1998–1999 climate of the southern Coast Mountains stands out in the contemporary record because of the exceptional amount of snowfall that accumulated through the winter season. Over 1 000 and 1 400 mm of precipitation was observed in the valley bottom and alpine areas, respectively, resulting in record snow accumulations of 167 and 467 cm. Temperatures remained near monthly normals for the year, and most regional snow courses also observed record snowpacks. Three large runoff events on Lillooet River occurred in 1999, all of which included a significant snowmelt component (Fig. 9). Daily flows during the freshet peaked at 584 $m^3 s^{-1}$ on 15 June 1999, following several warm days with light rain (this was the peak discharge event on record for Fitzsimmons Creek) (Fig. 2). A second snowmelt-driven event of 560 $m^3 s^{-1}$ occurred on 28 July 1999, following another short-term warm period. August was the only month where monthly temperatures were notably above average. A possible consequence of the exceptionally deep snowpack and high summer afternoon temperatures is an increase in the occurrence of wet snow avalanches triggered by solar heating. Such avalanches would have a high potential for sediment entrainment because of the large snow supply volume and high snow density. The peak summer rainstorm flood discharge of 649 $m^3 s^{-1}$ occurred on 24 August 1999 following a moderate one-day rainfall event. The 1999 hydrograph is the only year in the Lillooet River record with three separate flood peaks exceeding 550 $m^3 s^{-1}$.

As with the majority of the other years discussed, the 1999 varve can be separated into snowmelt and rainstorm components. The snowmelt component of the deposit consists of at least five separate graded beds (Fig. 9). These individual beds may be related to the numerous freshet flood peaks observed in the hydrological record. A partial clay cap overlies the snowmelt deposit, which was likely deposited during the falling limb of the freshet flood. The autumn rainstorm component of the varve consists of a thicker, slightly coarser, double-graded bed. The cause of the second sediment pulse to the site is unknown. It could be related to a sudden sediment entrainment into the fluvial system or a major, within-lake, turbidity current or slump. On average, the snowmelt flood signature accounts for 41% of the 1999 sedimentary unit in terms of deposit thickness. This is another example of significant sediment accumulation associated with moderately high-magnitude snowmelt and autumn rainstorm floods. The total amount of lacustrine sediment deposited in 1999 is 22 100 ± 2 600 Mg.

### *Other snowmelt flood events*

Both 1958 and 1999 were years that experienced moderately high snowmelt and autumn rainstorm floods. The largest three snowmelt freshet floods observed in the contemporary Lillooet River record occurred in 1968, 1997, and 1969, with peak flood discharges of 790, 676, and 640 $m^3 s^{-1}$, respectively. Varves deposited during these three years are similar in thickness and appearance and are all thicker than the aver-

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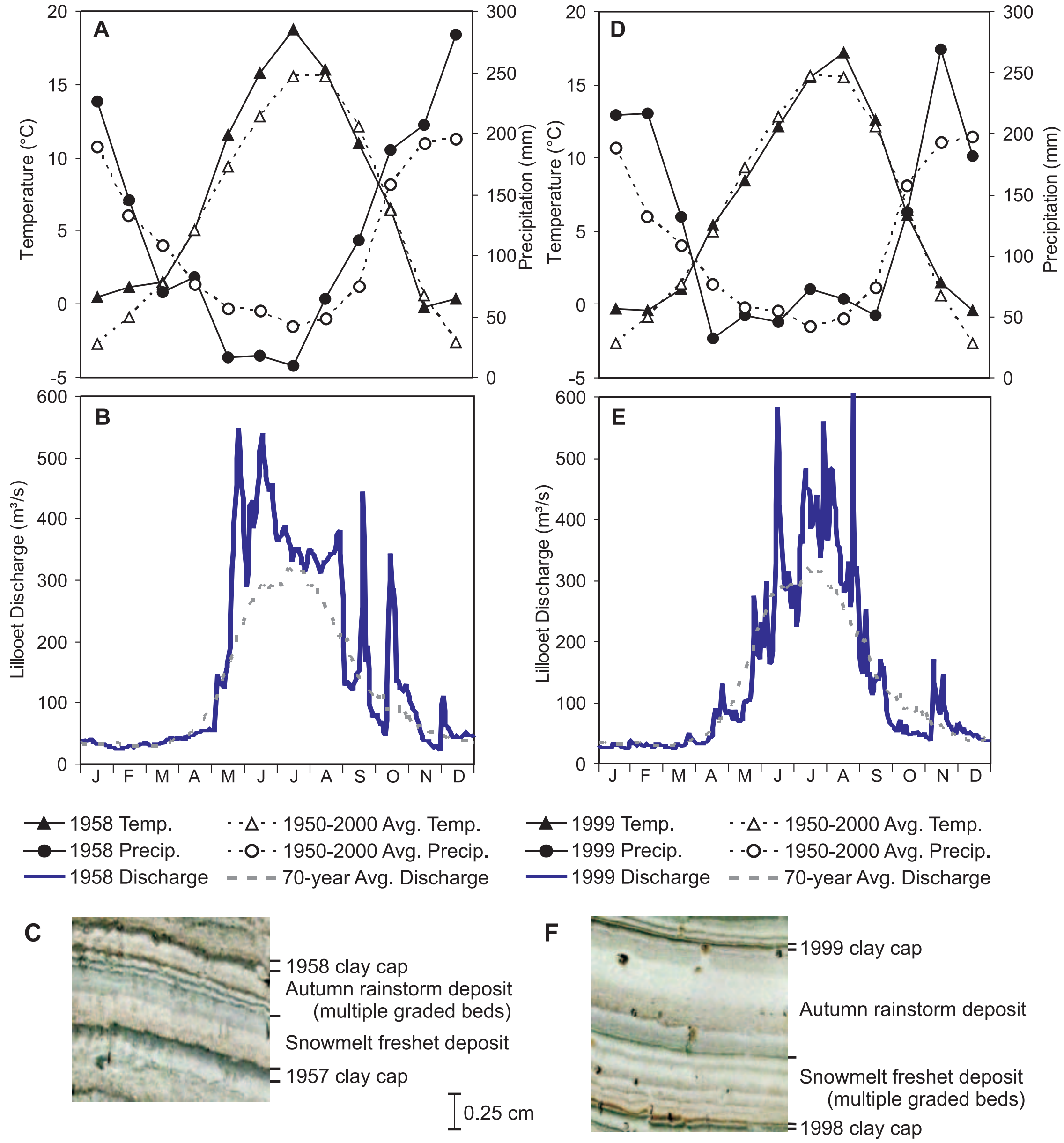
**Fig. 9.** (A) and (D), Whistler monthly temperature and precipitation for years 1958 and 1999, respectively. (B) and (E), Lillooet River hydrographs. (C) and (F), interpreted sediment-core images from site 2.




age, due primarily to unusually thick snowmelt deposits (all three years also experienced minor rainstorm floods). The total amounts of lacustrine sediment deposited in Green Lake during these major snowmelt flood years ranges between 13 000 ± 5 500 and 10 000 ± 3 900 Mg $a^{-1}$.

## Comparison of events

Major depositional episodes in Green Lake during the contemporary period are associated with autumn rainstorm events, years of rapid glacier recession, and unusual snowmelt conditions. Annual deposits of major autumn rainstorm years typically exhibit a relatively coarse-grained, multiple-component, rhythmic signature. A partially developed clay cap separates the rainstorm flood deposit from the underlying snowmelt freshet component of the varve. The amount of intermediate clay deposition depends on the duration of late summer – early autumn low flows between the high freshet discharges and the autumn event. Most of the event deposits consist of several graded beds of varying thickness and texture in the upper portion of the varve signature. These multiple graded beds are interpreted to reflect short-term fluctuations of flood flow discharges or sediment delivery, inflow, and delta configuration changes, or other modifications to lake circulation patterns. Late-season storm deposits have a distinctive brownish colour and contain more organic debris. It is likely that valley bottom regions of the catchment increasingly dominate contributing sediment source areas during these events, resulting in more localized deposition near the Nineteen Mile Creek inflow. Relatively thick winter clay caps generally overlie storm event deposits. Varves deposited during years of unusual snowmelt conditions, including major

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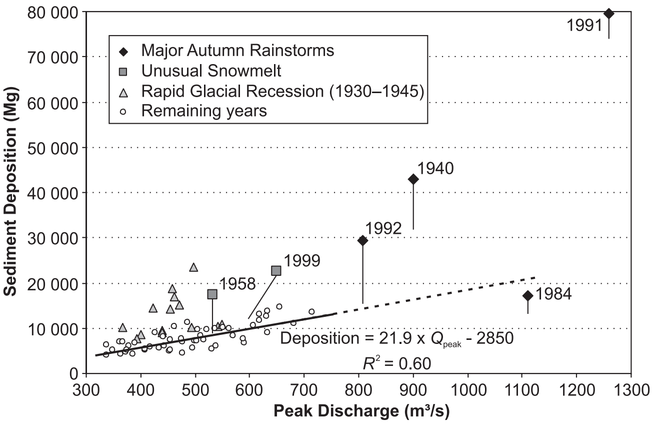
**Fig. 10.** Relation between annual sediment deposition in Green Lake and the Lillooet River annual maximum daily discharge. Extreme autumn rainstorm and unusual snowmelt years are labeled. Regression model is for average regime years (excludes labeled rainstorm and snowmelt years and identified years of rapid glacier recession). Lines below labeled event points show plotting positions for the post-snowmelt freshet and pre-rainstorm intra-varve components for the major rainstorm and unusual snowmelt condition varves, respectively.




snowmelt floods and highly sustained freshet discharges, exhibit a thicker snowmelt component bed in the lower portion of the varve signature. This snowmelt component of the varve may consist of a single bed or multiple-graded beds, depending on the character of the freshet hydrograph. Varves deposited during years of rapid glacier recession (1930–1945) are stratigraphically distinctive and significantly thicker than varves deposited post-1945 (Mann–Whitney rank sum test: $t$ = 771.0, $p$ < 0.01). These 1930–1945 sediments are denser, less organic rich, and finer grained than sediments deposited over that last 60 years. This may reflect elevated clastic sediment delivery from glaciers and proglacial sources during the earlier portion of the contemporary period. Whereas individual rainstorm and snowmelt floods produce relatively discrete events in the sediment record, periods of rapid glacier recession result in more continuous, inter-annual anomalies as newly exposed proglacial surfaces become prolific sediment sources. Air temperature also controls the inter-annual pattern of glacier runoff and long-term behavior of glaciers. The relation between glacier runoff and air temperature may explain the relation between thick varves and air temperature anomalies observed for proximal, shallow locations in Green Lake (Menounos 2006). However, this relation between temperature and lake sedimentation is not apparent in deeper portions of the lake where a major component of sedimentation is delivered by underflow events (Schiefer 2006*c*).

A positive, linear relation is observed between peak discharge and lake-wide sediment deposition for the contemporary period if the years that experienced major autumn rainstorms, unusual snowmelt conditions, and rapid glacier recession are excluded (Fig. 10). Similar relations have been observed in other glaciated lake catchments of the southern Coast Mountains (Gilbert 1975; Desloges and Gilbert 1995; Menounos et al. 2005). Anomalously high sediment accumulation is observed during most of the identified extreme-regime sediment delivery years. Some rapid glacier recession years plot within the normal-regime scatter, and the major autumn rainstorm of 1984 did not result in anomalous sediment deposition relative to its flood magnitude. The unusually high deposition during the other major rainstorm events may have resulted from additional geomorphic effects, such as the deep-seated landslide failure caused by the 1991 rainstorm, continued channel response to the 1991 event during the 1992 rainstorm, and the rapid glacier recession preceding the 1940 autumn rainstorm. The unusual snowmelt years of 1958 and 1999 also exhibit anomalously high sediment deposition, although this appears to be largely related to coinciding moderate autumn rainstorm events in addition to atypical snowmelt conditions. Only the major rainstorm intra-varve deposits of 1940 and 1991 plot well above the established background deposition–discharge sedimentation trend.

## Conclusions

The "normal-regime" depositional record, as defined by Desloges and Gilbert (1994), could be calibrated as a hydroclimatic proxy in a relatively straightforward manner for the Green Lake catchment (Fig. 10). Unfortunately, extreme-regime sedimentation events are more difficult to interpret as a paleoenvironmental record for the catchment because of the broader range of associated hydroclimatic controls and additional confounding geomorphic effects. Extreme-regime sediment delivery and deposition for the contemporary period (1930–2000) is associated with three primary types of hydroclimatic forcing functions, including rapid glacier recession of the 1930s and early 1940s, major autumn and late-summer rainstorm events, and unusual snowmelt conditions during the early spring and summer. Stratigraphic characteristics vary among events of different type and magnitude. In most cases, event signatures can be associated, at least partially, with the coinciding instrumental record of hydroclimatic conditions. Greatest lake-wide rates of sediment delivery in Green Lake are related to extreme late-summer and autumn rainstorm floods. Other geomorphic processes, including large landslide failures within Quaternary valley-fill material and major channel destabilization effects, can also be linked to elevated lacustrine sedimentation rates. Years of anomalous sedimentation are the result of singular events of an exceptional nature or multiple discrete episodes of sediment delivery.

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