Forest Renewal BC Research Program

Final Report

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Cover page: Cesium ($^{137}$Cs) activity levels as a function of depth for core 97-Duf(10). Maximum (7.5 cm depth) and onset (9.5 cm) of activity correspond to sedimentary couplets deposited in the lake basin between 1960-1965 and 1950-1956AD confirming the varved nature of the central basin sediments of the lake. Air photo shows natural (snow avalanche) and forestry (cut blocks and roads) examples of disturbance that influence rates of sediment delivery to the lake basin.
Summary

The degree to which production and mobility of fine-grained sediment within medium-scale watersheds has been altered by forestry-related disturbance has been neglected. This research question provided the focus for an intensive, three-year study which combined contemporary monitoring with a retrospective analysis to determine the severity of forestry-induced disruptions of sediment production and discharge from the Duffey Lake watershed, a 250km² catchment within the Coast Mountains. Despite terrestrial evidence for the disruption of the fine-sediment cascade within the watershed following the onset of forestry, an unequivocal signal of land use could not be detected with a lake sediment approach. Changes in the characteristics of the sediment obtained from the central lake basin are recognized for one to three years following road construction but decadal-based estimates of sediment yields are similar to yields before disturbance and yields from a control catchment (Birkenhead) during similar epochs. Based on data obtained from contemporary monitoring of sediment and water fluxes to the lake basin, it appears that changes in climate and the presence of glacial cover within the catchment have been the most important factors which have influenced yields to the lakes for at least the past 70 years.

From the coherence of secular trends and departures observed in long-term records of sediment flux obtained from lakes with only small to moderate percentages of ice cover (Duffey, Birkenhead, Lower Joffre and Green Lakes) it appears that century-scale climate variability has had profound importance in controlling sediment delivery to the lake basins for at least the past four millennia. From a management perspective, these results suggest that in catchments with only minor vestiges of contemporary ice cover, the detection and assessment of land-use effects from lake sediments will prove difficult. It can be concluded that medium-scale watersheds, with contemporary ice cover as low as 2-3 percent, will show less disturbance to the sediment production regime than those where glacial cover is absent. Whereas previous work within non-glaciated watersheds indicates detectable changes in the sediment regime when 25 percent of the watershed is logged, this study suggests a potentially higher threshold for watersheds where sediment transfers conform to an “event” rather than “supply-limited” sediment cascade model.

Further work is required to determine whether lake-based methods are applicable for understanding the effects of land use within medium-scale, mountain watersheds without glacial cover.
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Introduction

A detailed understanding of how timber harvesting practices impact water and sediment fluxes within mountain watersheds is necessary for sustainable use of British Columbia’s forests. Numerous studies within North American, Pacific Coast forests have demonstrated that excess sediments of natural and human-induced origin are detrimental to aquatic and terrestrial biota. Although the effects of forest management on water regimes in small catchments have been investigated in detail, little is known about the cumulative effects of forestry practices on accelerated sediment production in larger systems.

Sustainable forestry also requires a better understanding of how sediment production, mobility and discharge from watersheds is controlled by climate variability. Changes in climate often invoke dramatic variations in sediment and water discharge from mountain watersheds entirely independent of human-induced disturbance. Regional-based reconstruction of how sediment discharge has varied through time provides an important and necessary means of controlling for climate variability when assessing whether human-induced disruptions of water or sediment cascades have occurred.

The report summarizes the results of a study which specifically investigated how scale and climate variability have influenced the fine sediment discharge within a moderately disturbed mountain watershed within the Coast Range of British Columbia. The methods used to quantify these changes rely on the recovery and analysis of lake sediments obtained from lakes located at basin outlets. Retrospective, paired-watershed experimental designs have proved useful for documenting disruptions of fine-sediment cascades following forestry-related disturbance [e.g. 1]. In addition to determining whether the quantity or physical characteristics of the sediment are different following land use, an intensive monitoring program was undertaken to understand how contemporary climate influences sediment production, mobilization and discharge over short (days-to-years) time scales. Finally, those changes attributable to land use were compared to longer, more robust records of sediment discharge developed for the region.
The Study Area

The Duffey (disturbed) and Birkenhead (control) catchments are separated by approximately 30km and located in the Cayoosh Range of the Coast Mountains (figure 1). The watersheds (approximately 250 km$^2$ in area) straddle a major hydro-climatic divide separating the more maritime ranges to the west from the drier, interior mountains. Both watersheds are comprised of similar vegetation and bedrock and morphometric relationships of the basins are comparable (table 1). Evidence of geomorphic processes which are thought to be important for the production and entrainment of sediment such as percent glacial cover, landslides, debris flows and snow avalanches appear to be similar between the watersheds.

Forestry activity and general land use within the Duffey Lake watershed began in 1970 when a logging road was constructed which joined the towns of Pemberton and Lillooet. This road was initially constructed for timber extraction but jurisdiction and maintenance was transferred to the Ministry of Highways in the late 1970s. In 1990 the Duffey Lake road was resurfaced with asphalt thereby minimizing one potential source of fine sediments to the lake basin. Forest Harvesting was moderate in the early 1970s within the catchment and was concentrated along the valley floors of the Cayoosh and Van Horlick Stream systems. Approximately 8.6 percent of the catchment has been logged. During the late 1970 and 1980’s timber harvesting moved further up the mainstem reaches of the Van Horlick and Cayoosh creeks. As of 1994, total road length in the Duffey catchment totaled 121.7 km or a density of 0.48 km km$^{-2}$. The Duffey Lake Road makes up 17 percent of this total while logging companies have built and continue to maintain the other 83 percent. Although timber harvesting has taken place since 1994 those areas were not on the available forestry cover map sheets.

In contrast to the Duffey Lake catchment, minimal land use disturbance has occurred within the Birkenhead Lake Catchment. Approximately 1 percent of the catchment has been logged (based on 1994 forestry cover map sheets) and the catchment road density is 0.09 km km$^{-2}$. 
Figure 1. a) Duffey and Birkenhead catchments; b) Coring location and bathymetry. Depths are in meters.
Table 1. Morphometric Characteristics of the watershed and lake basins.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Duffey Catchment</th>
<th>Birkenhead</th>
</tr>
</thead>
<tbody>
<tr>
<td>Catchment Area (km²)</td>
<td>255</td>
<td>204</td>
</tr>
<tr>
<td>Relief (m)</td>
<td>1615</td>
<td>1886</td>
</tr>
<tr>
<td>Ruggedness # (km((km²)^0.5))</td>
<td>0.10</td>
<td>0.13</td>
</tr>
<tr>
<td>Stream Density (km km⁻²)</td>
<td>0.50</td>
<td>0.56</td>
</tr>
<tr>
<td>Highest Stream order</td>
<td>3 (Van Horlick;Cayoosh)</td>
<td>4 (Sockeye)</td>
</tr>
<tr>
<td>Major Stream Length (km)</td>
<td>21 (Van Horlick)</td>
<td>19 (Sockeye)</td>
</tr>
<tr>
<td>and Gradient (m km⁻¹)</td>
<td>43</td>
<td>81</td>
</tr>
<tr>
<td>2nd (km)</td>
<td>19 (Cayoosh)</td>
<td>11 (Phelix)</td>
</tr>
<tr>
<td>Gradient (m km⁻¹)</td>
<td>66</td>
<td>116</td>
</tr>
<tr>
<td>Percent Glacier Cover</td>
<td>1.6</td>
<td>1.35</td>
</tr>
<tr>
<td>Lake Area (km²)</td>
<td>3.7</td>
<td>4.1</td>
</tr>
<tr>
<td>Maximum Depth (m)</td>
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<td>38</td>
</tr>
<tr>
<td>Mean Depth (m)</td>
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<tr>
<td>Volume (km³)</td>
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<td>0.10</td>
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<tr>
<td>Trap Efficiency</td>
<td>95</td>
<td>88</td>
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<tr>
<td>Catchment Area/Lake Ratio</td>
<td>67</td>
<td>54</td>
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<tr>
<td>Logged Area (percent)</td>
<td>8.6</td>
<td>1.4</td>
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<tr>
<td>Road Density (km km⁻²)</td>
<td>0.48</td>
<td>0.01</td>
</tr>
</tbody>
</table>

Methods

-Monitoring of Stream Flow and Climate

Water and sediment fluxes within the streams and to the lake floor were monitored continuously throughout the study period (May 1997- November 1999). Water level (stage) and temperature were collected on a 10-minute sampling interval on three of the four major stream entering the lakes between August 1997-August 1999. Stage was converted to discharge by rating curves developed during the summer and fall months following standard procedures [e.g.2]. Shielded thermistors (±0.5 °C) and tipping buckets rain gauges recorded air temperature and precipitation within each basin to document meteorological events important for runoff generation within the catchments.

Determining contemporary sources of fine-grained sediment to the lake basins was determined by periodic collection of suspended sediment samples from the trunk and tributary streams within the catchments. Samples were obtained by collecting depth-integrated samples
(using a DH-48 depth-integrating water sampler) throughout each hydrologic season. Sufficient turbulence at the sampling localities minimized lateral suspended sediment concentration gradients producing samples that reflect average vertical and horizontal sediment concentrations [3]. Water samples were vacuum filtered (0.45 μm) and the remaining sample mass was oven dried (105 °C) to determine sediment concentration (mg l⁻¹).

-Contemporary Monitoring of the Sediment Flux to the Lake Floors

In June 1997, two oceanographic sediment traps were installed in proximal and distal locations with respect to major stream inlets within each lake (figure 1b). Each trap is constructed of two settling chambers with interior baffles mounted vertically 2 m above the lake floor which provide flux rates (g m⁻² day⁻¹) to the lake bottom by particle settling. Contemporary sediment fluxes from turbidity currents are not monitored but can be assessed within the lake coring design of this study. The traps were emptied four times yearly at the start of each hydrologic season and provided important data concerning: a) the hydrologic season most responsible for the highest sediment fluxes to the lake floors; b) the year-to-year variations in sediment delivery to the lake; and c) between-lake comparisons of contemporary sediment fluxes.

-Lake Sediment Recovery and Analysis

The spatial distribution of sediments within the lake basins were determined by recovery of over 60 sediment cores. Long cores (2.0 -7.7m) were recovered from the deepest portions of the lakes during the winters of 1996-1997 and 1997-1998 from lake ice with a percussion coring device [4], and a vibracoring system [5]. Shorter cores (10-15cm) were obtained during the summer from a boat with a gravity corer and by sub-sampling Ekman dredges [c.f.6]. Warm temperatures during the winters of 1997 and 1998 did not allow long cores to be recovered from Birkenhead Lake due to inadequate ice thickness but an 80 cm gravity core (operated from a boat) was recovered from the distal portion of the lake basin.

Sediment cores were split, sampled at different spatial frequencies (1.0 cm for shorter Ekman cores and between 2.5-5.0 cm for longer cores), and subject to routine sedimentological analysis [7]. Bulk physical properties which were determined for the entire core suite include measurements of density, water content, carbonate, and organic matter content. Magnetic properties, carbon isotopes and particle size data were collected on both short and long cores from the central basin of Duffey Lake to investigate whether sources of sediment have changed
following land use. Magnetic measurements were completed at the Pacific Geoscience Center in Sidney, BC. Stable carbon isotope data were determined by technicians in the Department of Oceanography at the University of British Columbia.

Changes in the frequency type and character of sediments deposited during individual years was determined by embedding sediment slabs obtained from the shorter cores with low viscosity resin which were then dried, polished and observed petrographically [e.g. 8]. Sediment cores were also repeatedly photographed during drying as varves and laminations became visible [9].

Depth-age models of sedimentation into the lakes are provided by non-organic radioisotopes such as lead and cesium¹ [e.g. 6, 9], radiocarbon dating of terrestrial macrofossils (Duffey and Birkenhead), tephrochronology (Duffey), estimates based on contemporary sedimentation rates (sediment trap data) and by varve counting (Duffey). Accelerator mass spectrometry (AMS) was applied to determine the $^{14}$C activity of terrestrial macrofossils found within 1.0cm-thick slices of sediment. Calibrated ages were determined with the bi-decadal data set INTERCAL93 [10].

**Calculation of Sediment Delivery to the Lake Basins**

A method similar to Arnaud [1] was utilized to determine the quantity of sediment introduced to Birkenhead and Duffey Lakes before and after the onset of forestry. This procedure relies on calculating the mass of elastic matter delivered to the lake and requires the recovery and analysis of multiple sediment cores. The flux (kg m$^{-2}$ yr$^{-1}$ ) of elastic matter is determined for a core location and then multiplied by a representative area of the lake basin. Development of accurate depth-age models within non-laminated sediments is a significant challenge due to the financial cost of dating individual cores and inconsistencies in age estimates derived through radiometric methods [e.g. 1]. However, the presence of varved sediments within the central portion of Duffey, combined with lake-wide marker beds provides a means of assessing sediment yields to the lake basin on decadal time scales. Sediment yields for Birkenhead lake were determined by combining sediment trap flux rates with average sedimentation rates based on radiocarbon dating.

¹ We are currently awaiting results of $^{210}$Pb dating for Birkenhead Lake. An addendum to this report will be submitted if those data change the sediment yields estimated to Birkenhead Lake derived through other dating techniques employed.
Results

-Monitoring Program: Streamflow

The monitoring portion of this study provided important data concerning the climatological controls of sediment production and mobility within the Duffey and Birkenhead Lake catchments. Those findings indicate:

1) The three streams investigated in detail show excellent within and between catchment correlation (figure 2a). The similarities in the hydrologic response of these streams most likely arises from; a) close proximity and hence similar climatological forcing and, b) the majority of runoff from the catchment is derived from snowmelt rather than rain storms. Rainstorms within mountain environments often show higher spatial variability in precipitation intensity and storm totals because convection cells (km’s in area) may deliver the majority of precipitation. Conversely, snowmelt generated runoff is generally caused by synoptic-scale weather patterns which commonly affect large spatial regions.

2) Cayoosh Creek is the most “flashy” of the 3 streams (figures 2b, c) and for this reason it is hypothesized to be most susceptible to lateral instability during high discharge events. Its response time to climatological forcing is appreciably shorter than Van Horlick or Phelix Creeks and generally has the highest instantaneous discharge (when normalized for basin area). Physical evidence for lateral instability was noted during the peak discharge of 1999 (snowmelt in origin) when the channel eroded a large organic debris jam, and changed its thalweg position by some 30 m.

3) Although all 3 streams exhibit coherent patterns of fine-sediment discharge according to hydrologic (snowmelt, glacial melt, autumn precipitation events), the quantity of suspended sediment transport between channels is unique (figures 3a, b, c). Some of these differences can be explained by variability in active sediment source areas upstream of monitoring sites. For example the quantity of sediment transport for the Van Horlick is almost always greater than Cayoosh Creek except during extreme discharge events. Higher, non-event sediment transport rates most likely result from differences in
Figure 2. a) Yearly hydrographs for the Van Horlick, Phelix and Cayoosh Creeks with early season (1997) record interpolated (dotted). b) Hydrologic response to autumn precipitation event. Hydrographs normalized by catchment area. c) Snowmelt generated runoff event. Note abrupt decline in discharge (stage) following large woody debris jam collapse on 16 June 1999.
Figure 3. Discharge-Sediment Concentration relationships for Van Horlick, Cayoosh, and Phelix Streams. Dependence of the relationship in the Duffey Lake catchment is related to changes in sediment supply and water availability for transport. No decernable relationship exists for Phelix Creek.
channel sediment sources (Van Horlick is a tortuous meandering, sand bed river while the Cayoosh is a meandering gravel bed river). The poor relationship between sediment transport and discharge for Phelix Creek (figure 3c) can only be partly attributed to a less intensive sampling scheme. Random availability of fine sediment sources (e.g. channel bank collapse) may account for some of this scatter but it is also likely that a better relationship would appear if higher discharge events were effectively sampled. The negative correlation between discharge and discharge-transport variance is most likely the manifestation of variable sediment sources during times of the hydrologic season when stream flow is generally low.

4) The timing and type of precipitation event, and whether snowcover exists during a given hydrologic event are important elements which control whether the event is responsible for entrainment of non-fluvial sediment. High discharge events caused by snowmelt or precipitation events on snow (where snowcover in not exhausted) transports predominantly sediments found within or adjacent to the active stream channels and sediment discharge is proportional to water discharge (figure 3a). Other sources of sediments are not available for recruitment because rainsplash of exposed soil is not occurring (snowmelt) or because soil and road surfaces are protected by snow. Precipitation events which appear to be most responsible for recruitment of non-channel sediment include precipitation events during summer and autumn. These observations agree with work in other mountain environments [e.g. 11, 12].

The most effective sediment-transporting event appears to have been a precipitation event that occurred on 1 October 1997 when approximately 33-43 mm of precipitation fell during a 24 hour period. Maximum discharge was reached 3 hours (Cayoosh) and 6 hours (Van Horlick) after maximum precipitation intensity (4.25 mm hr\(^{-1}\)). Although precipitation totals for this storm were moderate, pre-event flows in both creeks were elevated from a precipitation on 30 September. Total precipitation between 29 September and 4 October, 1997 was approximately 100mm (figure 2b). All of the precipitation within the basins fell as rain and no snowcover existed immediately preceding the event. This precipitation event produced bankfull discharges in both Cayoosh and Van Horlick Creeks. Bedload movement was audible in both creeks during peakflow. The discharge event mobilized non-fluvial sediments within the catchment in addition to elevating mobility of bedload and in-stream fine-grained sediment. High sediment concentrations were measured in water samples taken
Figure 4. a) Box and whisker plot of sediment concentration by basin. Horizontal lines within boxes are median values and square symbols are sample averages. Box bottom and tops represent 25 and 75 percentile of distribution, whiskers represent 5 and 95 percentiles; b) Median sample suspended sediment concentration versus percent glacial cover for monitored basins and sub-basins. Median value chosen to eliminate leverage effect of infrequent, extreme events on influencing the “non-event” sediment discharge from basins.
from road culverts within the Duffey Lake catchment. Observations during the storm revealed appreciable sheetwash erosion and rilling on many of the logging roads and road cutbanks within the catchment during the rain storm. Based on sediment yield estimates obtained from rating curves, the quantity of sediment transported between 29 September and 4 October was comparable in magnitude to the suspended sediment discharge for the previous months of August and September (1997). This suggests that, if antecedent conditions are right, (e.g. no snowcover and mild storm), autumn precipitation events are significant in mobilizing both fluvial and non-fluvial sediments within the catchments. Because of the importance of these autumn rainstorms in influencing sediment mobility within mountain watersheds of the province, further work should be directed understanding the spatial distribution of these high discharge events both as function of position and elevation.

5) Despite their limited extent (< 2 percent), glaciers appear to dominate the fine-sediment availability within the study watersheds both in a direct and indirect manner. During glacial melt (usually late summer), streams directly route fine-grained sediments (glacial rock flour) from regions of glacial cover to the lake basins. Coarser sediments (sand-sized material) can be traced up many of the channels that drain glaciated terrain. Based on similarities of lithology, these sediments appear to originate from glacial forefields and moraine complexes deposited during the Little Ice Age (ca. 300 yr BP) and during earlier glacial advances. This material, unlike glacial rock flour, is most likely entrained during higher flow events (e.g. snowmelt or precipitation events of sufficient magnitude) and thus, glaciers appear to indirectly "prime" channels draining small glaciers. The combination of immediate and intermittent routing of sediment leads to generally higher levels of sediment concentration, and by inference, higher sediment discharge from proglacial areas within the watersheds (figures 4a, b).
Figure 5. Seasonal flux rates to the lake floors. b) relation between flux rate and organic matter content.
Monitoring Program: Lake Sediment Fluxes

The 3 years of continuous monitoring of lake sedimentation revealed the following:

1) Maximum sediment fluxes appear to be most attributed to spring runoff but years of high glacial melt (e.g. 1998) or years with significant autumn rainstorms (1997) complicate a sedimentation model based solely on spring runoff (figure 5a).

2) There appears to be little temporal time lag between introductions of sediment from the watershed and sedimentation to the lake (figure 5a). The significance of lake overturning in influencing sedimentation fluxes was unknown but low sedimentation rates during autumn 1998 and 1999 helped to verify that most of the variability associated with sediment fluxes during fall is likely due to variations in the timing and severity of autumn precipitation events.

3) As expected, highest sediment fluxes are recorded closest to areas of major lake inflow (figure 5a). Individual sedimentation events undergo a seasonal transgression from mainly underflow (early snowmelt) to interflow and overflow events as the sediment concentration, stream and lake water temperatures undergo density fluctuations through the progression of the hydrologic cycle [13].

4) There is a good correspondence between sedimentation rates and the physical characteristics (organic matter content) of the sediments (figure 5b). The inverse relation between organic matter and sedimentation rates has been previously suggested for oligotrophic lakes [e.g. 14, 15, 16] but only by qualitatively suggesting that trends in organic matter content reflect changes in the terrestrial inputs of clastic matter. This study provides quantitative data which show that; a) the organic content of material which undergoes settling by suspension is non-linearly related to rates of sedimentation in an inverse manner; and b) the relationship is similar for both lakes. Further work is in progress to determine the generality of this relation for oligotrophic lakes within British Columbia because such a relation could be exploited as a preliminary technique for estimating sedimentation rates within lakes where fluxes to the lake floor are
Figure 6. a) Lake-based sediment yield estimates. Error bars (2 o) indicate variability of mass accumulation from the contributing cores. Number of contributing cores (n) is given for each yield estimate. b) Comparison of lake-based yields against fluvial derived yield estimates from Church et al. (1987). Trend line through data is proportional to catchment area to the 0.6 power.
dominated by inputs of catchment-derived, clastic sediment. This technique would allow first-order approximations of sedimentation rates before more elaborate (and costly) methods were utilized.

**Retrospective Approach: Sediment Yields to Duffey Lake**

Bulk physical properties necessary for determining sediment yields to the lake (density, loss on ignition of lake-productivity components) were completed on 19 cores mainly obtained by sub-sampling undisturbed Ekman dredge samples and with an additional longer core taken closer to the lake delta where sedimentation rates were believed to be higher.

Depth-age models for contemporary (75 years) mid-basin lake sedimentation within the lake were established by varve counting and verified by cesium (\(^{137}\)Cs) dating. \(^{137}\)Cs activity levels of 1.0 cm thick slices of sediment were determined for a short Ekman core (97-Duf(10)) collected from the deepest portion of the lake. Clearly-defined marker horizons with onset (1954) and peak (1963) activity levels were present in most Ekman samples. Other marker beds were located within the varved, central basin sediments and could be correlated across the entire lake basin.

The flux of clastic material to Duffey lake could be calculated for 7 specific time intervals from 1937 to the present. Two of these intervals correspond to periods after the onset of land-use disturbance. Selection of the intervals was entirely dependent upon recognition of "stratigraphic marker horizons" that could be correlated throughout the lake basin. Identification of these marker horizons was made by examining both color photographs of partially-dried sediment cores and the recognition of similar bulk physical property changes apparent within the sediment core suite. Many of the sediment cores (e.g. those closest to the lake delta) recovered only 30 years of sediment and it was necessary to use adjacent core flux rates to approximate the mass of sediment introduced to that portion of the lake basin. Although percent loss on ignition (550° and 950° C) values vary depending on the position in the lake and depth within a given core, the combined percentage of loss of mass due to organic and inorganic carbon is approximately 8 percent.

It appears that the quantity of sediment introduced to Duffey lake after the onset of land use disturbance is not significantly different from the natural variations in sediment delivery to the lake basin for the last 60 years (figure 6a). The average yield to the lake between 1937 and 1998 is 25.07 ± 3.1 Mg km\(^{-2}\) yr\(^{-1}\) and falls close to the main trend of fluvial-derived sediment yield estimates [17] for basins in British Columbia (figure 6b).
Figure 7. a) Changes in the bulk physical properties of the central basin sediments of Duffey Lake. Increases in SIRM/X ratios in the recent lake sediments are attributed to increased fluxes of lithologies adjacent to the lake; b) Secular trend and recent depletion of heavy carbon isotopes within the sediments of the central basin. Recent changes in climate and or changes in the flux of terrestrial organic matter are most likely responsible for most recent anomaly.
The period 1937-1946 has the highest sediment yields of any period but also has the fewest contributing cores and is therefore most susceptible to error. Sediments deposited during 1937-1946 are lower in organic matter content, finer grained and individual couplets can be traced throughout the central basin cores.

Although it would appear that sediment delivery to the lake basin has not undergone significant change following land-use effects, the lake based method of estimating sediment yields is limited by recognition of datable, identifiable marker horizons which occur throughout the entire lake basin. This may create a situation where very high initial rates of sediment flux (such as observed within the varved sediments of the central portion of the lake basin) are combined with later periods where sediment yields were lower possibly due to climatic controls.

-Retrospective Approach: Sediment Yield to Birkenhead Lake

Unlike Duffey lake, the upper 30 cm of sediments within Birkenhead lake are completely massive and most likely caused by bioturbation or current reworking. Based on modern sediment flux data to the lake floor and a single radiocarbon date obtained from one core 98-Birk(V), sedimentation rate estimates for the period 1937-1998 can be made for the proximal and distal basins. Depth-age models were verified for the cores by matching clastic sedimentation departures recognized within the cores to patterns observed in other lake sediment archives from Duffey, Lower Joffre, and Green Lake and assuming constant sedimentation rates. In order to facilitate comparison to Duffey Lake, sediment yields were calculated for similar epochs. Because marker horizons are absent within the sediments, these estimates are susceptible to appreciable error because of the uniform sedimentation rate assumption for each core. Assessment of this error is not possible without detailed dating of each core which is cost prohibitive.

Much like Duffey Lake, sediment yields are highest in the earlier portion of the record (figure 6a). The sediment within this interval of both lakes is denser, less organic rich and finer grained. The exact cause for this regional signal of enhanced sediment yields is unknown but rapid retreat of glaciers within both catchments is suspected. Glaciological studies on Vancouver Island [18] and elsewhere [19] indicate that Coast Mountain glaciers underwent rapid retreat from their Little Ice Age positions during the first half of the twentieth century. Glacial demise within the region was most likely caused by well-documented northern Hemisphere warming that began shortly after the turn of the century and lasted until about 1950AD [20]. Consequently,
these data suggest that sediment yields from glaciated Coast Mountain catchments were elevated during the third and fourth decades of the twentieth century due to glacial retreat within the region. Sediment yields to both lake basins have apparently undergone decline since the mid 1970s and most likely reflect both reduced glacial retreat and shallower mountain snowpacks (i.e. smaller spring runoff) within Southwest British Columbia [21].

-**Retrospective Approach: Changes in Sediment Properties Following Landuse**

Although the volume of sediment introduced to Duffey lake after 1970 is not statistically different than pre-disturbance levels, notable changes in the bulk physical properties of the sediments are recognized within the deepest portion of the lake following landuse (1970AD). Varves deposited in 1937-1954AD are predominantly silty, are lower in organic matter content and are characteristic of clastic varves deposited in proglacial lakes [e.g. 6, 22]. Between 1954 and 1970, the varves are more organic, coarser grained and no within-varve laminations are present. Contacts between individual varves are diffuse. After 1970 and until 1989 the varves show a pronounced increase in internal laminations. In particular, white silty laminae are present within varves deposited during 1970 and 1972. These deposits can be traced throughout the central and proximal lake basins where they form thick turbidites which increase in thickness toward the delta. The white silts are also present in the 1973 varve within the central basin but this deposit can not be traced throughout the lake basin. The thickness of this deposit declines non-linearly from 1970 to 1973.

Varve years 1970 and 1972 coincide with years of initial road construction (the Duffey Lake road) and major years of timber extraction from the watershed. It is most likely that very high sediment fluxes were delivered to the lake basin during these years. The source of these sediments was most likely fine-grained material mobilized within the watershed during road construction.

-**Retrospective Approach: Magnetic and Organic Matter Source Changes**

Magnetic susceptibility of sediment is related to the proportion of sample which can be magnetized and is most commonly related to magnetite content [23]. In lakes where the majority of deposited sediment is derived from the watershed rather than from in-lake productivity, changes in susceptibility mirror other changes in the bulk physical properties of the sediments because the volume of magnetite generally increases with increasing loading of clastic sediment. The degree to which samples remain magnetic after application of a strong magnetic field is
known as isothermal remnant magnetization (IRM) or saturated isothermal magnetization (SIRM) if they are put into a very high magnetic field. These magnetic parameters and ratios derived from them, can often detect changes in lithology or sediment type and hence, changes in sediment provenance.

Abrupt changes in sediment source are evident within the Duffey Lake sediments around 1500 cal yr BP. (~200 cm depth in core 97-Duf(09)) and after 1970 (figure 7a). Based on the magnetic properties obtained from fluvial, hillslope and glacial sediment samples, the earlier transition is believed to be the result of increased fluvial-sediment sources to the lake basin while the most recent transition reflects either reduced loading of fluvial-derived sediment or enhanced contributions of fine-grained magnetic lithologies (which are adjacent to the lake) to the lake basin during the last 30 years. Road construction and forestry activity along the south side of the lake basin is a probable reason for this change.

Changes in the type of organic material deposited within the lake basin has undergone both secular changes over the last 4000 years combined with a clear anomaly in recent years. A downcore increase in the proportion of heavy carbon ($\delta^{13}$C enrichment) is evident within two sediment cores from Duffey Lake (figure 7b). The factors which may have influenced this trend are unknown but most likely relate to changes in the proportion of terrestrial-derived organic matter to the lake basin and or increasing lake water temperature [24, 25]. The isotopic carbon signature of the sediments deposited after 1970 are anomalous when compared with the 4000-year record of organic carbon isotopic fluctuations for Duffey Lake.

Some of this observed change may result from enhanced productivity within the lake due to cooler surface water temperatures or reduced turbidity of the lake water. Turbidity is mainly controlled by changes in the proportion of fine-grained suspended sediment within the lake water. It is possible that reductions of yearly fine-grained sediment discharge to the lake basin following glacial retreat (discussed earlier) may have increased primary productivity (e.g. algae growth) within the water columns by lowering the turbidity of the lake water. If this hypothesis is correct, it would also explain why sediments which are more organic rich show greater evidence for bioturbation than sediments which are finer grained and generally organic poor.

Another plausible explanation for changes in the isotopic content of the recent sediments of Duffey Lake is that the proportion of terrestrial organic matter reaching the lake basin changed after timber harvesting began. The signature of carbon produced by terrestrial and lacustrine sources is often quite different [e.g. 26]. Due to the limited analysis
Figure 8. (a) Trends in organic matter content for Green, Birkenhead, Lower Joffre and Duffey lakes. Records smoothed with 5pt running mean filter. Note similarities in timing and prominence of century-scale variability.

(b) Calibrated radiocarbon ages of organic material found in forefields of Canadian Cordillera glaciers (names given) between 1000 and 3750 cal yr BP. Calendric age plotted at mid point of ± 1σ (68 percent) range of calibrated radiocarbon age. Numbers represent number of radiocarbon ages that were combined with the calibration program Oxcal and passed a chi-squared test for similarity at a probability level of 0.05. Gray rectangles are age ranges and number of samples associated with sheared in situ trees killed by advancing ice at Robson Glacier (Luckman, 1994). Age of terminal moraines within the Canadian Cordillera compiled from data in Desloges and Ryder (1990) and Osborn and Luckman (1988).
conducted, however, it remains unknown whether this anomaly is the result of recent climate change or changes in the magnitude of organic loading to the lake. Additional work should be directed to examining whether a carbon isotopic approach can be utilized to detect changes in the flux of terrestrial-derived sediments from watersheds affected by forestry practices.

-Retrospective Approach: Long-term Change in Regional Sediment Yields

Climate archives such as polar ice cores are commonly analyzed to assess whether current global warming is a natural or human-induced phenomenon. In much the same way, recent anomalies in the rates and type of sediment introduced to lacustrine basins within the Coast Mountains need to be compared to long-term records of sediment delivery in order to put recent changes in sedimentation into a longer, more robust perspective. Documenting past sediment-yield fluctuations are also helpful because sediment-yields within the region appear to be strongly related to climate [27] and thus, the analysis of these archives may provide clues into the magnitude, extent and recurrence of climatic features common to an area. A better understanding of these climatic cycles is paramount for understanding the dimensions of human-induced changes in contemporary climate and also provides important data which can be used by management (e.g. hydroelectric) or conservation (fisheries) personnel. The bulk physical properties from sediments of Duffey and Birkenhead lakes were analyzed in longer cores in order to characterize secular trends and departures in clastic loading to the lake basins over time scales that significantly exceed the length of climatological records from the region and elsewhere.

Duffey Lake organic matter content\(^2\) can be characterized by a millennial-scale waveform which is most apparent in core 97-Duf(09). Superimposed on this trend are centennial-scale negative departures in organic matter content centered approximately at 3600, 3100, 2800, 2600, 2400, 2200, 1950, 1500, 1250, 1050, 725, and 300-50 calendar years before present (2000 AD). Varves are thicker and clearly visible within these intervals of the Duffey lake cores where the organic carbon content is below average. The presence of clasts within several of these centennial-scale departures of organic carbon most likely represent dropstones resulting from snow avalanching onto the lake ice or directly into the lake. Consequently, these intervals of organic-deficient sedimentation into the lake are believed to reflect enhanced suspended sediment discharge during climatic periods favorable for glacial nourishment. Most of these

\(^2\) A proxy for sedimentation rates in an inverse manner.
periods of clastic sedimentation correspond to radiocarbon-dated glacial advances within the Canadian Cordillera (figure 8b).

Trends and periodicities in clastic loading within Duffey Lake show appreciable similarity to records of sediment discharge elsewhere within the region (figure 8a). Consequently, it suggests that century-scale fluctuations within the region are most likely caused by coherent variations in climate that have affected the southern Coast Mountains for at least the last four millennia. Work is in progress to develop varve-based chronologies of sediment loading to Green and Duffey lake to examine the year-by-year correspondence of sediment discharge between the lake basins over time scales of decades to millennia.
Discussion and Recommendations

Results from this study indicate that although a retrospective approach to characterize changes in sediment yields following forestry has shown success elsewhere, its applicability is contingent on the sensitivity of the catchment to record those changes and the severity of the land-use disturbance. In the Duffey lake catchment, a lake-based sediment approach detected no increase in sediment delivered to the lake basin following landuse within the catchment. It is hypothesized that sediment supply to the lake is “event” rather than “supply limited”. In this watershed, small percentages of contemporary ice cover provide appreciable volumes of sediment which can be transported directly to the lake during glacial melt or intermittently as fine-grained bed load within active stream reaches. Both glacial melt and bedload transport are highly contingent upon climate and meteorological events. The increased sediment supply caused by forestry appears to have been negligible when compared to the volumes of sediment produced and available for entrainment in the natural setting. It is likely that changes in sediment delivery following land use within medium-scale watersheds are detectable by using a lake sediment approach where sediment transfers conform to a “supply-limited” model. Other retrospective methods detailing change in the sediment cascade should be modified or developed to assess land-use effects in watersheds where changes in sediment discharge are controlled more by the variability in climatological events rather than changes in sediment supply. This is an important task because sediment transfers within a large number of managed watersheds within the province appear to conform to an event-limited sediment cascade model. Nevertheless, it should be realized that even within event-limited watersheds, detectable and significant changes in the production, redistribution or export of fine sediments could occur if the degree of disturbance is severe. From a management perspective, however, it remains a crucial task to better define the threshold at which landuse disruptions of the fine-sediment cascade have immediate and prolonged effects on natural ecosystem health.
Extension Activities

Dissemination of Data to the General Public

The data and results of this study will made available for the general public via the world wide web. A web-based, data and report access site is currently under construction.

Report to BC Parks and Dissemination of Information to Visitors

Much of this project’s work was completed in watersheds that are regulated by BC Parks. A copy of this report will be sent to Brandin Schultz, regional coordinator for the Sunshine District, BC Parks. Phelix Creek is the primary spawning habitat for Kokanee Salmon of Birkenhead lake and the streamflow data will be given to Parks or Fisheries for management purposes.

One of the most import results of this project is the discovery of a coherent signal of past climate change for the region. This information will be summarized and broadcast to visitors of the park by way of information placards or pamphlets.

Report to Ministry of Forests

Data, report and consultation will be given to personnel of Ministry of Forests.

Dissemination of Data to the Academic and Forest Management Community

The result of this study are currently being distributed to the scientific community by way of professional talks and manuscript writing to both academic and forestry-related organizations. FRBC is formally acknowledged within these outlets. Reprints of papers originating from work funded by this project will be forwarded to FRBC.

Forthcoming forestry symposia to be organized as part of extension commitment of FRBC Forest Hydrology Chairs (Dr. R.D. Moore and R. Sidle).
References


