Assessing Natural Sedimentation Patterns and Impacts of Land Use on Sediment Yield: A Lake-sediment–based Approach

ERIK SCHIEFER, KEVIN REID, ALAN BURT, AND JAMES LUCE

ABSTRACT

Lake-sediment records were used to investigate historical sedimentation patterns in 70 headwater lake catchments of northwestern British Columbia. Sediment-core chronologies and sedimentation rates were derived from $^{210}$Pb dating methods. Study objectives include the confirmation of lake coring and associated analysis techniques as appropriate methods for reconstructing past sedimentary environments, the assessment of the natural patterns of lake sedimentation, and the determination of the relative impact of forestry and other land-use disturbances on lake sedimentation in context with the naturally observed variability.

Several interesting lake-sediment records have been identified and reviewed. While there is a high degree of variability in the data set, several distinct trends were recognized. Regional analysis has revealed that specific sediment yield spans two orders of magnitude, from 0.55 t/km$^2$/y in the Interior Plateau to 52 t/km$^2$/y in the Coast Mountains. Lake basins are differentiated by physiography, both in terms of average specific sediment yield and dominant processes of sediment transfer, as indicated in the drainage-basin, area-specific, yield relations. Temporal analysis has indicated a trend towards increasing lacustrine sedimentation rates irrespective of land-use change in the study watersheds. This trend may be related to precipitation increases in the study area over the last several decades. Episodic natural disturbances are very important processes of sediment transfer in headwater lake catchments, especially in mountainous regions. Land-use impacts could be only partially separated from natural fluctuations; however, a signature of land use was observed in some of the study lakes that were exposed to high levels of land-use disturbance.

INTRODUCTION

It has long been established that land-use disturbances can induce elevated sediment yields in affected drainage basins. Increased sediment yields caused by forestry-related activities can have adverse effects on aquatic ecosystems in both streams (Scrivener et al. 1998) and lakes (Miller et al. 1997). Dominant processes, efficiency, and rates of sediment transfer vary greatly throughout the Pacific Northwest in response to topographic, geologic, and...
climatic factors (Swanson et al. 1987). The complex behaviour of sediment transfer in the Pacific Northwest holds profound implications in the study of how forestry affects sediment yield.

A major problem encountered in studying disturbed sediment yields in the Pacific Northwest is separating the forestry impacts from natural disturbances, given the high degree of natural spatial and temporal variability encountered. It has been demonstrated that the analysis of lake sediments can be useful for assessing land-use impacts on sediment yield at the basin scale, since a long-term sedimentary record can be established that reflects all of the integrated upstream watershed effects (Arnaud 1997). This is especially beneficial in remote mountainous regions where stream gauging and long-term monitoring is non-existent. In this study, lake-sediment records have been utilized to investigate historical sedimentation patterns in northwestern British Columbia. The specific project objectives are as follows:

1. Confirm the usefulness of lake coring and associated analysis techniques as appropriate methods of assessing long-term impacts of forest harvesting and other land-use disturbances on lacustrine sedimentation.
2. Assess the natural patterns of lake sedimentation, including regional trends, spatial scale effects, and temporal variability.
3. Determine the relative impact of forestry on lake sedimentation in context with the naturally observed variability.

The key premise of this study is that linkages exist between the inherent landscape characteristics and terrestrial disturbances (both natural and anthropogenic) of lake catchments and the quantity of accumulating lacustrine sediments. Lake sediments represent a historical record of sediment yield and sediment characteristics from the contributing drainage basin area. Petts and Foster (1985), Foster et al. (1987), and Foster et al. (1988) have reviewed and demonstrated the lake-sediment framework and its application in reconstructing past catchment conditions. When properly sampled and analyzed, the information recorded in the sediments can be extracted as profiles of historical lake sedimentation. Changes in sedimentation associated with land-use disturbance can then be identified and described.

The primary focus of this research is on the historical rates of lake-sediment accumulation derived from ${}^{210} \text{Pb}$ analysis of sediment core samples from the study lakes. ${}^{210} \text{Pb}$ dating is a commonly used technique for establishing sediment chronologies back to 150 years before present. A total of 70 lake catchments were selected for this study. The development and utilization of geographic information system (GIS) databases has been critical for handling the large amount of spatial data required for the project. A GIS database was developed to inventory the landscape data and land-use histories of the lake catchments. Extracted from this database were variables to describe the natural landscape and the land-use history for each study lake. These variables and the lake-sediment data were then analyzed to resolve the three study objectives listed above. The project can be divided into three phases:

1. Collection and analysis of lake-sediment cores in order to establish historical rates of sediment accumulation and measure other sediment parameters for the study lakes.
2. Development of a spatial lake catchment inventory in a GIS environment suitable for the extraction of required landscape and land-use indices for analysis.
3. Correlation analysis of GIS-derived indices with sediment accumulation rates and other sediment parameters in order to interpret regional sedimentation patterns.

This paper presents the key findings of the study to date. A more detailed examination of the data can be found in Schiefer (1999). Additional analysis of the data is currently being considered, including empirical modelling of sediment yield over both time and space using multivariate techniques.

GENERAL STUDY AREA

The study area is situated in northwestern British Columbia between 54° and 56° N and 126° and 131° W (Figure 1). Clague (1984) gives a detailed description of this region in a Geological Survey report on the Quaternary geology and geomorphology of the area. The study region consists mainly of rugged mountainous areas cut by deep valleys. The Coast Mountains contain the most spectacular mountainous terrain in the study area. Moving into the Nechako Plateau to the east, the terrain becomes more rolling with less exposed rock outcrops. Topography and the predominant flow of moisture-laden air from the west control precipitation in the study area, with the Coast Mountains receiving the highest annual precipitation during frequent mid-latitude cyclonic storms in the winter months. Most of the area below 1500 m was forested prior to human settlement, but large sections of accessible valleys and plateau areas have been cleared during the 20th century to support the forest industry and other land-use activities.

METHODS

Lake Selection

The British Columbia Ministry of Environment, Lands and Parks provided a preliminary list of several hundred potential headwater study lakes for this project. Topographic maps, lake inventory reports, and air photos of the region were examined in order to reduce the list of candidate lakes. Site selection involved consideration of lake suitability for a sediment-based, sediment-yield study based on lake morphometry and landscape characteristics of the lake catchment. Lakes had to be deep enough (preferably >10 m) to minimize the potential for physical reworking of sediments from waves, seasonal overturn processes, subaqueous slumping, and bioturbation by bottom-dwelling organisms. Lakes also had to be large enough to be accessible by floatplane and small enough that a single core will represent a fair and consistent index of sediment yield to the lake (i.e., approximately 1 km$^2$). Complex bottom morphology leads to greater within-lake spatial variability of sedimentation patterns, making estimates of sediment yield using a single core unreliable. Both landscape and land-use characteristics of the lake catchments were considered in the lake-selection process in order to ensure that the study lakes were well representative of lakes in northwestern British
FIGURE 1  Skeena region study area.
Columbia. First- to third-order catchments were selected from a variety of physiographic regions in the study area, including coastal, mountainous, plateau, and major valley regions. Unforested high-alpine and glacier lakes were not included in this study. Significant effort was also made to include lakes subjected to a gradient of forestry-related, land-use disturbances. Ultimately, field reconnaissance was used to determine the final list of study lakes. A total of 70 small lake-catchments (order of 10–100 km²) were selected for the project.

**Sediment Coring**

Coring of lake-bottom sediments using a modified Kajak-Brinkhurst (KB) gravity corer was a major component of the field work. A detailed description of the KB corer is provided by Brinkhurst (1974). Upon arrival on each of the study lakes, depth sounding was conducted along the entire length of the lake to characterize the basin. Sediment-sampling sites were always situated at the deepest point of the lake basin. Sediment cores retrieved from deep and stable sections of the lake bottom usually have the finest stratigraphic definition as a result of sediment focusing of the fine materials (Pack et al. 1997). Four cores were collected at each station for dry-bulk density analysis, ²¹⁰Pb dating, archiving, and a backup in case of loss. After all of the cores were collected, they were aligned to ensure that they were consistent in terms of apparent layering and other sediment characteristics. To visually assess the areal continuity of the lake-bottom sediments, additional cores were sampled at a variety of other mid-lake locations as time permitted.

Core extrusion and slicing was performed using the OCP Core Extruder. Sediment samples were extracted from the top of the core using a sectioning device. The core sub-samples were then washed into pre-labelled sample bags using distilled water, and submitted for laboratory analysis.

**Laboratory Analysis and Yield**

²¹⁰Pb dating is a widely used technique for establishing chronologies of lake-sediment cores. The ²¹⁰Pb analysis and reconstruction of historical sedimentation rates for the project was conducted by MyCore Scientific Limited. Details of the procedure used are presented by Evans and Rigler (1980), with modifications described by Cornett et al. (1984) and Rowan et al. (1994). ²¹⁰Pb is a naturally occurring radionuclide in the ²³⁸U decay series. ²¹⁰Pb formed by *in situ* decay is termed the supported component and is in radioactive equilibrium with parent material. The ²¹⁰Pb activity in excess of the supported component is primarily derived by direct atmospheric fallout into the lake, which is scavenged by sediment particles and deposited on the bed of the lake. The unsupported component decays exponentially in time in accordance with its half-life (22.26 years). It is this predictable radioactive decay of excess ²¹⁰Pb that provides the basis for dating lake sediments. The concentrations of ²¹⁰Pb were interpreted using the constant rate of supply (CRS) dating model (Robbins 1978; Appleby and Oldfield 1978). This model is generally preferred over other interpretation techniques because it allows for fluctuating rates in sediment deposition over time. The CRS model assumes that the input of excess ²¹⁰Pb to the sediment-water interface has remained constant through time and that no post-depositional migration of the radionuclide has occurred over the dating interval. The total quantity of excess ²¹⁰Pb (calculated by numerical integration of the ²¹⁰Pb profile) is used in the determination of sediment ages and sediment accumulation rates.

Using the calculated age and rate of sediment accumulation for the core sections, profiles of historical lake-sedimentation rates at the sampling site
can be developed. Sedimentation rates are best represented as horizontal lines plotted over core section intervals since the rate is an averaged measure across each section (several plots are included in this paper). Using this graphical representation, background lake-sedimentation rates were estimated. The background accumulation rate is assumed to be the component of the sediment load derived from primary denudation processes. Background sedimentation rates derived from $^{210}$Pb dating can be multiplied by lake area to obtain an index of total sediment yield from the contributing lake catchment area. The assumptions of areal continuity (the measured sedimentary property should be deposited in similar proportions over the whole lake-bottom area) and synchrony (once deposited, the measured property should be persistent and immobile) must be met for the calculated sediment yield to be a fair and consistent index of the actual sediment yield to the lake. The assumptions of continuity and synchrony of lacustrine sediments are common in lake-sediment–based literature. Since cores were taken from the deepest point of the lake, the index will likely be an overestimate of actual yield because of sediment focusing effects in the lake basin. In lakes with a flat bottom and less sediment focusing, the sediment-yield index will approach the actual yield. In order to make lake-to-lake comparisons of catchment denudation rates, the sediment-yield index can be converted to a specific sediment yield, or sediment yield per unit of contributing basin area.

GIS Database Development

Due to the large volume of spatial data used in the project, ARC/INFO GIS technology was used to facilitate data management and queries. Several key existing databases have been used as basic inputs to the GIS for landscape-level spatial analysis. The two most important sources of digital data include the provincial terrain resource information management (TRIM) maps and the British Columbia Ministry of Forests forest cover mapping (FGI). Several other basic inputs were used to verify the lake inventory, such as: GPS-recorded, field-sampling locations; aerial photography; available historical maps (road maps, recreation maps, fishery reports, etc.); and personal communication updates from B.C. Ministry of Forests and B.C. Ministry of Environment personnel.

Two types of variables were extracted from the GIS database. The first set of variables are landscape indices, which are considered static over the time scale of this study. These indices consist of lake-catchment morphometric parameters that relate to the sediment production, conveyance, and storage for the basin. Primary landscape variables include: basin area, lake/wetland/valley areas, stream length, and elevation/slope statistics. The second set of variables are dynamic (time-dependent) land-use indices. These indices consist of planimetric parameters of land-use change within the lake catchment that could relate to anthropogenic modifications to sediment transfer. The land-use indices are calculated on a yearly basis since the time of the first land-use disturbance. Primary land-use indices include area logged and road length (with various slope and distance-to-stream modifiers). Analysis of the landscape data consisted of regression with tests of statistical significance, which are based on the assumption that variables are normally distributed. Variables describing natural landscape characteristics are often log-normally distributed. Based on visual examination of variable histograms, the log transformation was deemed necessary for all landscape indices except for lake elevation and drainage density.
The first step in investigating trends in the sediment records was to assess the natural patterns of lake sedimentation by relating the $^{210}$Pb-derived sediment profiles to the landscape indices of the undisturbed lake catchments. This analysis was comprised primarily of standard linear regressions and analysis of variance. Secondly, the relative impact of land use on lake sedimentation was determined by relating the sediment profiles to temporal changes in the land-use indices for the disturbed lake catchments. This analysis was restricted to various semi-quantitative techniques, which are described in following sections. Based on these results, the usefulness of lake coring and associated analysis techniques as appropriate methods for determining long-term impacts of forest harvesting and other land-use disturbances on lacustrine sedimentation was assessed. Current knowledge of sediment transfer in British Columbia, and preliminary results in this study, suggest that sediment-delivery processes are strongly related to physiography and local geology. For this reason, most of the data set analyses were stratified for various physiographic units, as presented in the following section.

**RESULTS PRESENTED BY PHYSIOGRAPHIC REGION**

**North Coast Region**

Spectacular coastlines, steep-walled fjords, and rugged mountains characterize the region. Glaciated mountain peaks reach elevations in excess of 2000 m. Major rock-outcrop areas show fresh glacial landforms such as cirques, arêtes, and horns. Where bedrock is not exposed it is commonly thinly mantled by soil. Mean annual precipitation exceeds 2500 mm and in some areas surpasses 3500 mm. The North Coast study lakes were formed by glacial erosion in the mountains bordering the main valleys. They are medium-sized to large lakes with an elongated shape and very steep-sided bathymetry and immediate shoreline.

Background mid-lake sedimentation rates range from 49 to 2050 g/m$^2$/y. (Note: units of g/m$^2$/y are used to indicate rates of sedimentation per unit of lake basin area; units of t/km$^2$/y are used to indicate sediment yield per unit of the contributing catchment area.) The exceptionally high background sedimentation observed in some lakes reflects the large contributing drainage area, steep surrounding terrain, and close proximity to the Pacific Coast. Sedimentation rates in the North Coast lakes are highly variable over time. This reflects the episodic nature of sediment transfer in mountainous watersheds of British Columbia. The highest amount of variability is observed in lake catchments with an average slope greater than 30°. Possible land-use impacts could not be disentangled from the high degree of natural variability observed in this region.

**Hazelton and Skeena Mountain Regions**

The Hazelton and Skeena mountain ranges run north-south, parallel to the Coast Mountains. The Hazelton Mountains are bounded by the Kitsumkalum-Kitimat Trough to the west and the Kispiox and Bulkley rivers to the east. The Skeena Mountains are further inland between the Skeena and Bulkley rivers and the Nechako Plateau. Bedrock intrusions are not as widespread and relief is more moderate than that observed in the Coast Mountains. Some lake catchments contain high-alpine areas that remain snow-covered for most of the year. Precipitation is strongly controlled by orographic effects in this region. Mean annual precipitation ranges from
over 3000 mm on the windward side of the Hazelton Mountains to about
500 mm on the leeward side of the Skeena Mountains. Pleistocene sediments
impound all lakes in this region, although bedrock and active delta areas
along the shorelines are not uncommon. Lake sizes and shapes are highly
variable. Wetland areas are common in close proximity to the study lakes.

Background mid-lake sedimentation rates range from 40 to 600 g/m²/y,
largely controlled by the size of the contributing area. As observed in the
Coast Mountains, episodic events dominate sediment transfer in many of
the lake catchments. Elevated rates of lake sedimentation following land-use
disturbances have been observed in most catchments, up to double the ob-
served background levels. There is no obvious pattern between the degree of
disturbance and the magnitude of the sedimentation increase. In most cases,
sedimentation rates had been increasing before the onset of the land-use dis-
turbances. Furthermore, about half of the control lakes also show a
consistent increasing trend in mid-lake sedimentation rates beginning
around 1950. This natural trend of increasing sedimentation over the last half
of the century confounds the land-use signal, so the degree to which forestry
activities have influenced downstream sedimentation is undetermined.

An interesting lake-sediment signature was observed in Aldrich Lake, lo-
cated about 12 km west of Smithers on the opposite side of the Hudson Bay
Range. A watershed map and sedimentation rate profile with the timing of
land-use development in the catchment are included in Figure 2. Road and
mine development began north of Aldrich Lake in the early 1920s. Produc-
tion was intermittent between 1930 and 1940, but by 1950 the mine operated
at its highest production rates. The final year of operation was 1954.
Mid-lake sedimentation rates in Aldrich Lake increased steadily from a
background rate of about 300 g/m²/y to close to 700 g/m²/y during mine op-
eration. Sedimentation rates reached their highest levels of 780 g/m²/y in the
decade following mine production. This peak in sedimentation was likely as-
sociated with road failures and a blowout that occurred in the old tailings
dump. Sedimentation rates dropped in the following years, but then again
started to increase when forestry activities began in 1984.

Areas classified in this region include low-lying depressions and large valley
flats located between major mountain ranges. The Nass Basin and the
Skeena, Bulkley, and Kispiox valleys comprise most of this area. Rivers
presently occupy these regions, but during Pleistocene glaciation they served
as channels down which glacier ice moved. The region contains hummocky,
rolling, and undulating terrain underlain by thick Quaternary sediments.
The broad valley bottoms range from 200 to 500 m in elevation and have
gentle relief. Climate ranges from the maritime environment of the coast to
the continental climate of the interior. Most of this region is road-accessible
and has been subject to timber-harvesting activities. The lakes in this region
are relatively small compared to those in the other study regions. The lakes
located in the major valleys are impounded by thick Pleistocene deposits.
Lakes in the Nass Basin occupy low plateaus in a series of glacially scoured
troughs running northwest-southeast. Wetlands and low-lying swampy areas
are also common around the lakes. Distal to the lakes are high-relief moun-
tainous areas.

Background mid-lake sedimentation rates range from 16 to 186 g/m²/y.
Lakes with larger contributing areas generally have higher sediment-loading
rates, although sedimentation rates are not well predicted by any linear
Drainage area = 25.9 km²
Lake area = 0.82 km²
Lake depth = 5.5 m
Elevation = 1146 m
Road density = 0.99 km/km²
Percent logged = 7.6%

**Figure 2.** Aldrich Lake. SAR is sediment accumulation rate in g/m²/yr, road density is given in km/km², and amount logged is given as a ratio to drainage basin area.
combination of landscape variables. Half of the control lakes show an increasing trend in sedimentation in the latter half of their sediment records (50–100 years), a similar trend to that observed in the Hazelton/Skeena region lakes. Most disturbed lakes have experienced an increase in sedimentation coinciding with road construction and timber harvest. The lakes with the highest number of stream crossings had the greatest increases in sedimentation. Although almost all lakes have higher sedimentation rates following the forestry activities, several of the control lakes in the region show a similar trend in recent accumulation rates.

Elizabeth Lake is the only lake that clearly shows a recovery of sedimentation rates following completion of land-use disturbances back to background levels. A map of the lake catchment and a plot of sedimentation rates and land-use history of Elizabeth Lake are shown in Figure 3. Notice that sedimentation rates begin to increase immediately following the initial road construction in the lake catchment. Sedimentation rates continued to rise while road construction continued and logging began north of the lake. The highest sedimentation rate of 374 g/m²/y (307% above background) occurred 2 years following the most major road construction and significant logging in the catchment in 1980. Sedimentation rates began to recover when road construction in the basin was completed. Some timber-harvesting activities continued through the falling limb of sedimentation.

The Nechako Plateau is the only extensive plateau region in northwestern British Columbia. The Bulkley River extends southeastward into the Nechako Plateau, a rolling region with elevations ranging from 800 to 1200 m. The Nechako Plateau is bordered on the west by the Hazelton Mountains and to the north by the Skeena Mountains. The Nechako Plateau makes up part of the Interior Plateau region of British Columbia. The climate of Nechako Plateau is continental, and is characterized by seasonal extremes of temperature and moderate annual precipitation. This region contains the least dramatic relief of all of the study areas. Flat-lying volcanic strata and glacial drift overlie older bedrock in this region. Rivers flow in deep, glacially modified valleys cut into the rolling uplands. Lakes and wetlands dot the landscape in poorly drained, post-glacial depressions. Most of this region is road-accessible and has been subject to timber-harvesting activities. The largest range of lake and lake-catchment sizes is found in this region. Lake basins are fairly regular in shape and are relatively shallow compared to the lakes in the other study areas. Low-lying and poorly drained peat bogs, marshes, and swamp areas are common. Small lakes and ponds are abundant in the study catchments, many being held behind old beaver dams. There are no signs of hillslope coupling in the relatively flat terrain of this region.

Background mid-lake sedimentation rates range from 30 to 280 g/m²/y. As observed in the other regions, lakes with a larger contributing area generally have higher sediment-loading rates. However, similar to the Nass Basin and Major Valleys region, background sedimentation rates are not well predicted by any linear combination of landscape variables. Lakes in the Nechako region show similar patterns of sedimentation as observed in the Nass Basin and Major Valleys. Half of the control lakes have had increasing sedimentation rates over the last several decades. This natural increase in sedimentation rates has been observed in about half of the control lakes in this study, making interpretation of the effects of land use on the sediment signatures significantly more difficult because the timing of this increasing
**Figure 3** *Elizabeth Lake.*

- **Drainage area:** 21.8 km²
- **Lake area:** 0.46 km²
- **Lake depth:** 11.5 m
- **Elevation:** 415 m
- **Road density:** 1.23 km/km²
- **Percent logged:** 34.4%
trend coincides closely with land-use impacts. Again, all but a couple of the lakes that have experienced forestry-related, land-use disturbances have coinciding increases in their sedimentation rates. Catchments with greater land-use disturbances generally show greater increases in sedimentation, but this relation does not hold for all lakes.

Takysie Lake is a large lake located well within the Nechako Plateau in the southeast corner of the study area. The Takysie catchment has been subject to a long and diverse land-use history. The lake catchment and sediment profile are included in Figure 4. Sedimentation rates in Takysie Lake have been increasing since 1865, the earliest date available from the $^{210}Pb$ analysis. Most of the increase has occurred following road construction, timber harvest, and other land-use activities, including animal grazing, agriculture, residential development, and resorts/camping. The time of first land-use disturbance is unknown, but most development is known to have occurred since 1930, primarily to the west of the lake. The sediment profile does not reach a level background rate. $^{210}Pb$ analysis done in a paleolimnological assessment of Takysie Lake by Reavie and Smol (1998) indicated a background sedimentation rate of about 30 g/m²/y. This background rate fits the trend observed early in our sediment record. Both results showed a similar increase in sedimentation rates over the latter part of the century. Our results gave a higher peak-sedimentation rate of 269 g/m²/y compared to about 210 g/m²/y in their study. Sedimentation rates have increased 600–800% above background in Takysie Lake over the last 150 years. Not all of this increase can be linked to land use because rates were increasing before land-use activities began in the catchment. However, an increase of this magnitude is unprecedented for the lakes in this study. Reavie and Smol (1998) attributed the increasing sedimentation rates to lake eutrophication caused by elevated nutrient input from human development surrounding the lake.

**REGIONAL PATTERNS OF LACUSTRINE SEDIMENTATION**

**Within-lake Variability**

A minimum of four cores were sampled from the deepest point of the central basin of each lake. Whenever possible, additional cores were taken at points located elsewhere in the lake basin. A visual comparison was made in the field between all the cores taken from each lake. If the sediment cores contained visual markers (event layers, varving, change in sediment character, etc.), then the assumptions of areal continuity and synchrony of the lake sediments could be verified. Lake sediments must have these properties for cores to be representative of deposition across the entire lake. If the assumptions of areal continuity and synchrony are valid, sediment properties in order will be consistent and sediment will be deposited in similar proportions over the whole lake area. Cores from the same lake should then all have a similar and consistent sediment structure. There were no cases where the assumptions of areal continuity and synchrony of lake sediment did not appear to be valid for mid-lake areas. The focusing of sediment to deeper lake areas was evident because the distance between horizons in the sediment cores usually decreased as cores were sampled in shallower water. In lakes with a relatively flat bottom, the distance between horizons would increase as cores were sampled closer to the main inflow to the lake. The deepest spot in these lakes would not have been the optimal sampling location for obtaining the best temporal resolution in the lake-sediment analysis. Cores taken in
Drainage area = 185.6 km²
Lake area = 5.15 km²
Lake depth = 8 m
Elevation = 928 m
Road density = 0.9 km/km²
Percent logged = 18.7%

FIGURE 4  Takysie Lake.
shallower water and from near-shore locations would not always have a stratigraphy similar to that of the mid-lake cores. This was especially true in cores that were sampled on steep, lake-bottom slopes, above the lake thermocline, or on a delta front. These sediments are subject to re-suspension and transport by sub-aqueous slumping, water currents, and wind/wave action. Lakes best suited for this study have a well-defined and deep central basin, with a relatively flat bottom that is out of the influence of deltaic and near-shore processes. Lakes were selected that appeared to best meet these requirements in order to help assure areal continuity and synchronicity of the lake sediments. This was reflected in the high degree of correlation between mid-lake sediment cores.

Seven of the study lakes had varved over a segment of their sediment cores. All the varved sediments were from North Coast lakes or from lakes in the northern portion of the study area. This suggests that the presence of glaciers and strongly contrasting summer and winter hydrologic conditions are important factors in the development of varving. All the lakes were strongly stratified at the time of sampling and had good sediment-focusing characteristics. A comparison of averaged sedimentation rates derived from $^{210}$Pb dating and annual varve counting is provided in Table 1. There is a high degree of correlation between the averaged sedimentation rates calculated using both methods. The $^{210}$Pb calculated rates are slightly greater in six of the seven lakes. This bias may indicate a minor error in the estimation of the background $^{210}$Pb concentrations used in the sediment accumulation-rate calculations. Nevertheless, the high agreement between the relative and absolute chronologies improves our confidence in the dating techniques used.

### Regional Variability

Background sediment yield is a measure of the volume of sediment being deposited in the lake basins. Investigating relations between the sediment yield and landscape characteristics of the contributing basin is useful for developing predictive equations for estimating sediment yield in the general study area. This can be done using easily obtainable drainage basin parameters, thus avoiding costly field-sampling programs. Although this type of empirical analysis does not prove any cause-and-effect relations between sediment yield and landscape characteristics, these non-causal relationships may

<table>
<thead>
<tr>
<th>Study lake</th>
<th>Core segment (cm)</th>
<th>Averaged estimated sedimentation rate (g/m²/yr)</th>
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<tr>
<td></td>
<td></td>
<td>$^{210}$Pb dating</td>
</tr>
<tr>
<td>Toon</td>
<td>1–19</td>
<td>418</td>
</tr>
<tr>
<td>Amoth</td>
<td>14–30</td>
<td>273</td>
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<td>Unnamed KM1</td>
<td>18–20</td>
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<td>Jade</td>
<td>8–9</td>
<td>1075</td>
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<tr>
<td>Alpha</td>
<td>6–12</td>
<td>60</td>
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<td>Dragon</td>
<td>4–6</td>
<td>470</td>
</tr>
<tr>
<td>Mitten</td>
<td>2–4</td>
<td>147</td>
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represent important prologues to further theoretical understanding of the underlying physical processes of sediment transfer. A stepwise linear regression was performed with background sediment yield estimated from the $^{210}$Pb dating of the sediment cores (dependent variable) and all the GIS-derived landscape indices for the lake inventory (independent variables). The regression was run for each physiographic region and for the entire data set. The regression results, including the ANOVA of the regressions, are presented in Table 2.

All of the regression line slopes are highly significant ($P = 0.001$). In all cases the drainage basin area is the most important predictor variable. Sediment yield in the North Coast region is well predicted by the contributing drainage-basin area. Total valley-flat area and drainage density were important variables in the Hazelton and Skeena mountain regions, respectively. Valley-flat area is a term describing storage potential in the catchment. Valley-flat area is defined as the sum of continuous, flat-lying (less than $1\degree$ slopes) land and water-body (upstream wetlands and lakes, excluding the study lake) areas in valley-bottom areas of the lake catchment. These are areas where net accumulation of sediment occurs. Therefore, catchments with large valley-flat areas are more likely to have lower sediment yields, hence the negative influence on yield in the Hazelton Mountains. Conversely, drainage density had a positive influence on yield in the Skeena Mountains as a term that describes the transport capacity of a catchment. Since fine sediment is transported in suspension through stream channels, catchments with greater stream lengths per unit area will more efficiently transfer mobilized sediment from the land surface, through the stream network, to the receiving lake downstream. Sediment yields in the Nass Basin and Major Valleys region and in the Nechako Plateau region are not well predicted by any linear combination of the landscape indices. With the complete data set, drainage-basin area and mean slope of the catchment were the most significant predictor variables. It is not surprising that slope emerged as a significant variable in the all-regions regression. Average slope of a catchment relates to both storage

<table>
<thead>
<tr>
<th>TABLE 2</th>
<th>Background sediment yield regression and ANOVA results</th>
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<tbody>
<tr>
<td><strong>North Coast</strong></td>
<td><strong>Nass Basin and Major Valleys</strong></td>
</tr>
<tr>
<td>$\log(Y) = 0.76 + 1.38\log(A_b)$</td>
<td>$\log(Y) = 1.09 + 0.51\log(A_b)$</td>
</tr>
<tr>
<td>$n = 9, R^2 = 0.86$</td>
<td>$n = 18, R^2 = 0.46$</td>
</tr>
<tr>
<td>F Value: $\log(A_b) \rightarrow 43.5^{***}$</td>
<td>F Value: $\log(A_b) \rightarrow 13.7^{**}$</td>
</tr>
<tr>
<td><strong>Hazelton Mountains</strong></td>
<td><strong>Nechako Plateau</strong></td>
</tr>
<tr>
<td>$\log(Y) = 0.19 + 1.43\log(A_b) - 0.66\log(VFA)$</td>
<td>$\log(Y) = 1.42 + 0.43\log(A_b)$</td>
</tr>
<tr>
<td>$n = 16, R^2 = 0.83$</td>
<td>$n = 21, R^2 = 0.47$</td>
</tr>
<tr>
<td>F Values: $\log(A_b) \rightarrow 50.7^{*<strong>}, \log(VFA) \rightarrow 11.2^{</strong>}$</td>
<td>F Value: $\log(A_b) \rightarrow 16.6^{***}$</td>
</tr>
<tr>
<td><strong>Skeena Mountains</strong></td>
<td><strong>All Regions</strong></td>
</tr>
<tr>
<td>$\log(Y) = 1.12 + 1.84\log(A_b) + 0.62DD$</td>
<td>$\log(Y) = 0.59 + 0.77\log(A_b) + 0.52\log(slope)$</td>
</tr>
<tr>
<td>$n = 12, R^2 = 0.84$</td>
<td>$n = 76, R^2 = 0.66$</td>
</tr>
<tr>
<td>F Values: $\log(A_b) \rightarrow 39.3^{**<em>}, DD \rightarrow 8.3^{</em>}$</td>
<td>F Values: $\log(A_b) \rightarrow 134.1^{*<strong>}, \log(slope) \rightarrow 8.0^{</strong>}$</td>
</tr>
</tbody>
</table>

Where: $Y$ is the background sediment yield (Mg/yr)  
$A_b$ is the area of the drainage basin (km\(^2\))  
$VFA$ is the total valley flat area upstream of lake including water bodies (km\(^2\))  
$DD$ is the drainage density (km/km\(^2\))  
Slope is the mean slope of the land surface area (degrees)  

$* P < 0.05$  
$** P < 0.01$  
$*** P < 0.001$
potential (negatively—sediment accumulation is more likely in flat-lying terrain) and transport capacity (positively—steep terrain is more likely the source or transport area of sediment) of the basin. It is unclear if the regression results for all regions combined makes sense when the regional component regressions yield different results, which implies the possibility of different underlying physical processes in the different regions. It is interesting to note that the $R^2$ values are the highest in the mountainous areas (North Coast, Hazelton Mountains, and Skeena Mountains). The greater storage potential of sediment in the flatter catchment areas (Nechako Plateau, Nass Basin, and Major Valleys) may be confounding the predictability of sediment yield.

Specific sediment yield, or sediment yield per unit of contributing basin area, is used as an index of primary subareal denudation of the lake catchments. Lake-to-lake and regional comparisons in catchment denudation rates can be made using specific yield, since it accounts for basin scale and areal focusing of sediment into the receiving lake. Specific yield ranges from 0.55 t/km$^2$/y in the interior, to 52 t/km$^2$/y in the Coast Mountains. The average specific yield for all the lake catchments is 10 t/m$^2$/y. The average specific yields for the different physiographic regions are plotted in Figure 5. ANOVA indicated a statistical difference in the regional specific yield means. Using Tukey’s test (alpha = 0.01), the North Coast region was shown to have a statistically greater mean specific yield compared to the other regions. The higher rate of sediment yield per unit area in the North Coast reflects the higher erosion rates due to the greater transport capacity and lower storage potential in that region. These characteristics of the North Coast region are reflected in the landscape variables of mean slope and valley-flat area shown in Figure 6. The North Coast lake catchments have significantly steeper slopes and less valley-flat area than the other study regions.

In British Columbia, using suspended-sediment-load data obtained by the Water Survey of Canada, Church and Slaymaker (1989) observed a pattern of increasing specific sediment yield at all spatial scales up to $3 \times 10^4$ km$^2$. This trend results from the dominance of secondary remobilization of Quaternary sediments from streambanks and valley-bottom areas over primary

![Image](image_url)

**Figure 5** Regional differences in specific sediment yield.
denudation of the land surface. This result indicates that sediment yield of larger drainage basins remains conditioned by the extraordinary glacial events of the Quaternary Period, where large quantities of unconsolidated sediments were delivered to the major valleys of British Columbia (Church and Ryder 1972). This pattern controverts the conventional model of specific sediment yield, in which increased sediment storage downstream dominates sediment-transfer processes. As drainage area increases, a greater proportion of the mobilized sediment load is supposed to become trapped in the downstream cascade of storage zones on footslopes, floodplains, and in low-energy water bodies such as lakes and wetlands. There is no specific yield–drainage area relation in the lake-sediment–derived data as a whole. However, some interesting patterns emerge when the data are stratified physiographically, as shown in Figure 7.

Plot A in Figure 7 shows spatial trends in specific yield for the North Coast study catchments. These are high-energy systems that contain very steep terrain and receive large amounts of precipitation. Upland slopes are thinly

\[ \text{Plot } A \text{ in Figure 7 shows spatial trends in specific yield for the North Coast study catchments.} \]

\[ \text{These are high-energy systems that contain very steep terrain and receive large amounts of precipitation. Upland slopes are thinly} \]

\[ \text{Error bars show 2 standard errors} \]

\[ ** \text{Significant different from other groups (Tukey's test, alpha = 0.01)} \]

\[ \text{FIGURE 6 Regional differences in mean slope and valley-flat area of study catchments.} \]
(a) Coast Mountains

\[ Y = 0.016A^{0.38} \]

\[ R^2 = 0.32 \]

\[ n = 9 \]

\[ F\text{-value} = 3.53 \]

Positive allometry

(b) Hazelton and Skeena mountains

\[ Y = 0.020A^{0.00} \]

\[ R^2 = 0.00 \]

\[ n = 20 \]

\[ F\text{-value} = 0.00 \]

(c) Lowlands and Nechako Plateau

\[ Y = 0.037A^{-0.41} \]

\[ R^2 = 0.41 \]

\[ n = 33 \]

\[ F\text{-value} = 22.08^{***} \]

Negative allometry

Notes:
- Catchments from transitional areas have been removed (10 catchments dropped)
- Dashed lines are 95% confidence intervals of fit
- Significance of F statistic: ’ p < 10^{-1},” p < 10^{-2},”” p < 10^{-3}

**Figure 7** Specific sediment yield as a function of drainage area.
mantled, with large areas of exposed bedrock. Storage potential is low, since there is relatively little flat terrain in the contributing catchments of the lakes. Sediment yield increases with drainage area for lake catchments in this region. Sediment yield is roughly proportional to \((\text{drainage area})^{0.4}\). This fits the Church and Slaymaker (1989) model of sediment yield where remobilization of Quaternary sediment dominates sediment transfer in the basin. Pleistocene deposits on lower valley slopes (fans and aprons) and valley-bottom areas are likely the predominant sediment sources for lakes in the North Coast region. Plot C in Figure 7 shows spatial trends in specific yield for the Nechako Plateau, Nass Basin, and Major Valley study catchments. These are much lower energy systems with gentle relief and a drier continental climate. Upland slopes are mantled by thick glacial deposits. Lakes, wetlands, and broad valley-flat areas are common upstream of the study lakes. Storage potential is, therefore, quite high in these areas. Sediment yield decreases with drainage area for lake catchments in these regions. Sediment yield is roughly proportional to \((\text{drainage area})^{-0.4}\). This trend fits the conventional model of sediment yield where sediment mobilized from upland areas goes back into storage on footslopes, floodplains, and water bodies further downstream. Plot B in Figure 7 shows the spatial yield pattern for the Skeena and Hazelton mountain study catchments. The landscape characteristics of this region are intermediate to the regions discussed above. No scale-related trend in yield was detected in these catchments; in other words, specific yield is in a state of constant proportion with drainage area. This pattern of specific sediment yield does not clearly fit either of the two models mentioned previously. In all regions the range of specific sediment yield spans an order of magnitude at all spatial scales, likely the consequence of local geology. The reader is directed to Schiefer (in press) for a more detailed discussion of physiographic controls on sediment yield in British Columbia.

**Temporal Variability**

Sediment transfer in headwater catchments of British Columbia is commonly dominated by large-scale episodic events, in which large volumes of sediment are flushed through the system over relatively short periods of time. These high-magnitude/low-frequency events include processes such as mass wasting, streambank failures, and breaking of log jams. In the case of lake sedimentation, autochthonous processes could also be the cause of large fluctuations in sedimentation rates, including physical and biological events such as turbidity currents off a slumping delta front, or changes in lake productivity. The analysis of these disturbances is restricted because the sampling techniques lack the temporal resolution to properly capture these events, especially if they occur early in the sediment records. Another problem in dealing with these low-frequency disturbances is that the sedimentary records are too short to address the overall importance of these events in drainage basin sediment transfer.

Over a third of the study lakes had a significant peak (any recorded sedimentation rate approximately 100% or greater above the estimated background rate) in their sedimentation-rate profile without the influence of any land-use activities occurring in the basin. While these peaks in the sedimentation rates may be indicators of significant natural disturbances in the lake catchment, the specific causes of these fluctuations are unknown. These occurrences are most common in the mountainous regions, although they are observed in all regions. A closer look at the sediment profile of Shea Lake, a lake with a well-captured disturbance event, is made in Figure 8. Over a 19-year period (1929–1948), sedimentation rates in Shea Lake increased to a
peak rate 10 times greater than background. During that time about half of the total sediment load since 1920 was deposited in the lake basin.

Many of the sediment records show a significant increase in lake-sedimentation rates over the latter half of the century. This trend has been observed in all study regions. Of the control lakes, 11 of 23 clearly show this increasing trend in sedimentation rates, with increases ranging from 30 to 167% above background levels. Some lake catchments that have had land-use disturbances show the same increasing trend beginning before the onset of land use in the catchment. On average, sedimentation rates have been increasing irrespective of land-use change in the study lakes for the last 50 years. This could be a response to climatic change in the region. A relationship between sedimentation rates and precipitation would be expected, since the hydrologic cycle is the major driving force in sediment transfer. To investigate this possibility, precipitation records for the region (Prince Rupert, 89-year record; Terrace, 85-year record; and Smithers, 55-year record) have been analyzed. Cumulative departure plots were used to identify periods of above- and below-normal annual precipitation (Figure 9). An increasing
Figure 9 Cumulative departure plots for Skeena region precipitation.
trend in sedimentation rates would be expected to coincide with above-average periods of precipitation. The plots for Prince Rupert and Terrace show a similar pattern of below-average or average precipitation for the first half of the century followed by above-average precipitation. Both locations have also experienced precipitation significantly above normal for the last 20 years. Smithers, which is located in the interior portion of the study area, shows a different pattern in annual precipitation: rates have been above normal for the periods 1955–1965 and 1987–present, with an intervening period of below-normal precipitation between 1965 and 1987. These plots show that precipitation has been above average in the coastal areas for the last 50 years, and considerably above average over the entire region for the last 15–20 years. This indicates that the increasing trend in sedimentation rates may be, at least partially, a consequence of climatic trends in northwestern British Columbia. Storm-frequency analysis has not been carried out on the precipitation records. Since peak runoff events are often the result of the combination of complex hydro-climatic processes (including cyclonic storms, spring snowmelt, and rain-on-snow events), stream discharge records could be more useful in studying the occurrence of important sediment-transporting flood events. Unfortunately, few long-term discharge records are available in the study area, especially in headwater drainage basins.

The majority of lake catchments in this study have been subject to road construction and timber-harvesting activities. Most of these activities have occurred in the last couple of decades. In most cases a significant increase in mid-lake sedimentation rates has coincided with these land-use disturbances. However, since about half of the control lakes have also had an increase in sedimentation rates over the last few decades, the extent to which forestry has affected lake sedimentation is uncertain. Of the lakes in the control set, 48% (11 of 24) have had a recent increase in sedimentation rates. The average increase was 90% above background rates, with a maximum observed increase of 167%. For lakes that have been subject to road construction and timber harvesting, 84% (32 of 38) have had increasing sedimentation rates. The average increase was 137% above background rates, with a maximum observed increase of 307%. The largest recent increases in sedimentation rates have occurred in lakes of the Nechako Plateau and the Nass Basin and Major Valleys regions. These are the regions that have also experienced the greatest amount of forestry activity because of their less-rugged terrain and greater accessibility. Overall, lakes that have had road construction and timber harvesting in their watersheds have experienced greater increases in mid-lake sedimentation rates than the control lakes. In addition to forestry, other major land-use disturbances have occurred in two of the study catchments. A mining operation was active north of Aldrich Lake from the early 1920s to 1954. Human settlement began west of Takysie Lake early in the century and was followed by ranching, agriculture, residential development, and resort/camping activities. The sediment records for both Aldrich and Takysie lakes show significant increases in sedimentation over the duration of these land-use disturbances. Although sedimentation-rate increases coinciding with land-use disturbances are easily identified, they are well below the maximum relative increases observed, which are likely associated with natural geomorphic events.

The recent natural trend of increasing sedimentation rates observed in about half of the control lakes is a major confounding effect in the inter-
tation of land-use signals in the sedimentary record. To separate, to some extent, this trend and natural episodic events from the sedimentation rate profiles, the graphs in Figure 10 were developed. The first graph plots the departure of sedimentation rates from background levels for control lakes using smoothed lines with large peaks filtered out. The remaining profiles of control lakes were used to define an envelope of naturally occurring sedimentation rates. The wedge-shaped envelope clearly shows the increasing trend in sedimentation rates observed in many of the control lakes over the last 50 years. Beyond the envelope limits are regions defined as having unusually high and low sediment-accumulation rates. The second graph shows

**Figure 10** Separating land-use impacts from natural variability.
the departure from background sedimentation for lakes that have had land-use disturbances in their contributing catchment areas. No disturbed lakes plotted below the lower envelope limit. Thirteen lakes were identified as having unusually high sedimentation rates because they plotted above the upper envelope limit. These unexpectedly high sedimentation rates are likely related, at least partially, to land-use disturbances in the lake catchments. Most of these lake catchments are relatively small and have been heavily logged (generally over 20%) and roaded (generally over 1 km/km²) with some harvesting activities located immediately adjacent to the lake and contributing stream channels. This is a reasonable expectation—small watershed areas with extensive land-use coupled to the hydrologic network are the most sensitive to disturbance, although it should be noted that there were some catchments fitting these criteria that did not experience an unusually high sedimentation response.

CONCLUSIONS AND FUTURE WORK

Lake-sediment sampling and analysis has been utilized to investigate historical lacustrine sedimentation patterns in northwestern British Columbia. Seventy lake catchments were selected for study that span a range of spatial scales, physiographic regions, and land-use histories, in order to permit a comprehensive regional assessment of sedimentation trends and patterns for the study area. The primary focus in the study has been on historical rates of lake-sediment accumulation derived from $^{210}$Pb analysis of sediment core samples from the lakes. Variables to describe the landscape and land-use histories were extracted from a GIS database developed to inventory the study catchments. The key findings are reviewed in the four points below:

- There is a clear trend towards increasing lacustrine sedimentation rates irrespective of land-use change in many of the lake catchments. About half of the control lakes in the study clearly show increasing sedimentation rates over the last 50 years, with increases ranging from 30 to 167% above background levels. This natural trend is a major confounding factor in disentangling land-use impacts on sedimentation patterns. This trend may be related to precipitation increases undergone in the whole study area over the last few decades.

- Natural disturbances, such as mass wasting and other geomorphic events, are important processes of sediment transfer in headwater lake catchments. Sedimentation-rate profiles from all physiographic regions show some periods of disturbed sediment accumulation where accumulation rates are temporarily elevated many times above background levels. These occurrences are most frequent in mountainous regions. A large amount of the total sediment load delivered to lakes can be deposited over relatively short periods of time during these episodic events.

- Lake basins are differentiated by physiography, both in terms of average specific sediment yield and dominant processes of sediment transfer, as indicated in the relation between drainage basin area and specific sediment yield. Highest sediment yields were observed in the North Coast mountains where specific sediment yield increases with increasing drainage area. This trend is likely associated with the dominance of
secondary remobilization of Quaternary sediments from streambanks and valley-bottom areas. In the flat-lying plateau and major valley areas, specific sediment yield decreases with increasing drainage area, thus fitting the conventional model of sediment delivery where storage efficiency increases downstream. In the Hazelton and Skeena mountains there is no significant relationship between specific yield and drainage area. These results suggest that no single sediment-yield model is adequate in describing the sediment-transfer processes in British Columbia at the sub-regional scale.

- Superimposed on all of the observed natural variability are some qualitative and semi-quantitative land-use effects on sediment yield. Land-use impacts could be only partially separated from natural fluctuations; however, a land-use signature, in the form of increased sedimentation rates, was observed in some of the study lakes. Largest increases have occurred in heavily harvested and roaded lake catchments in the Nechako Plateau and the Nass Basin and Major Valley regions. Significant increases were observed in basins that were subject to multiple land-use disturbances.

There are many ways in which this current research on lake sedimentation in northwestern British Columbia could be improved and further expanded. Temporal trends may be better explained by looking at storm frequency and flood-discharge records for the region. All of the catchment information in this study was based on remotely sensed sources, primarily aerial photographs. It would be useful to expand the field component and include more detailed aerial-photograph analysis in future projects to conclusively determine, and perhaps quantify, the sediment sources, transport capacity, intermediate storage sites, and lake-storage efficiency in the lake-catchment sedimentary system. This would be beneficial in establishing underlying physical processes and cause-and-effect relations between catchment conditions and lake-sediment signatures. There would be many advantages in expanding this project to a multi-core study format for a sub-set of lakes. A single-core approach was used because the large number of lakes included in the study would have made a multiple-core approach impractical because of the much higher associated costs and time requirements. A multiple core study would enable a better assessment of within-lake spatial variability, which is important in lakes with more complex morphometries. Errors associated with the $^{210}$Pb dating and other measurements could be better described if replicate cores were available. A major advantage with the multiple-core approach is that absolute sediment yields could be estimated to a much higher degree of accuracy. The study could also be expanded to include a greater range of spatial scales and physiographic regions. Study results indicated that the relationship between the drainage basin area and specific sediment yield is variable in the different physiographic regions in northwestern British Columbia. This relationship is linked to downstream storage effects and remobilization of Quaternary sediment deposits, and holds major implications for geomorphological theory and for studies on land-use effects on the sedimentary system. It would be useful to expand the study data set so that the specific sediment-yield models for the province could be further refined.

The database of lake-sediment–based profiles of sediment yield, coupled with the operational GIS inventories of the contributing catchment areas, is a valuable and unique data set. To the knowledge of the authors, a comparable
database of long-term, sediment-yield patterns and historical catchment conditions does not exist. It is anticipated that additional information about sediment-transfer processes in lake catchments can be extracted from this database by the use of more advanced statistical analysis. The next step of this ongoing research project is to use multivariate techniques to develop empirical models to predict sediment-loading rates in both the natural and disturbed state for lake catchments in northwestern British Columbia. The ultimate goal is to establish a set of tools to be used by operational planners to help minimize the impact of proposed land-use management activities on aquatic lake ecosystems.

ACKNOWLEDGEMENTS

Special thanks are due to many people without whose help and support this research would not have been possible. We would first like to thank Ian Sharpe, Impact Assessment Biologist, B.C. Ministry of Environment for having the foresight to initiate this project, and for his continued guidance. Lisa Westenhofer provided contract administration and liaison services with the Forest District offices. We greatly appreciated the assistance of staff in the Forest District offices of Bulkley/Cassiar, Morice, Kispiox, Kalum, North Coast, and Lakes; they provided valuable insights that helped in the lake-selection process and they reviewed mapping materials for accuracy. The B.C. Ministry of Forests generously provided TRIM and FC1 data for the project, coordinated by Peggy Anderson of B.C. Ministry of Forests Digital Data Sales. Adam Cottrill, Paul LePage, Solvej Patschke, and Maritta Prent provided field assistance. Jack Cornett of MyCore Limited carried out the $^{210}$Pb analysis.

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REFERENCES


Reavie, E.D. and J.P. Smol. 1998. Paleolimnological assessment of Tchesinkut, Takysie and Francois lakes, British Columbia. Prepared by Paleoenecological Environmental Assessment and Research Laboratory, Department of Biology, Queens University, Kingston, Ont. for B.C. Ministry of Environment, Smithers, B.C. Unpublished.


______. In press. Physiographically controlled allometry of specific sediment yield in the Canadian Cordillera. Geografiska Annaler Series A.

ABSTRACT

A regional study was made of landslides in portions of the Arrow Forest District and the Kootenay Lake Forest District, which permits some preliminary conclusions to be made about the areal frequency of landslides, their causes, and their importance as sediment sources to streams. The study covered all or parts of 100 map sheets, totaling about one million hectares. Approximately 1700 landslides were inventoried by air-photo interpretation. A subset of about one-quarter of this study area, centred on the Slocan Valley, is discussed in this paper.

The data show that landslide frequencies are typically increased by roughly 10 times by forest development (depending on how one defines the land base for calculation of areal frequencies). The landslide frequency on private land is higher than on Crown land. About 95% of development-related landslides are due to roads or skid trails. On older roads, road-fill failures are apparently the most common cause. However, on newer roads, the most common cause is drainage concentration and diversion by roads. An important category of landslides occurs some distance below roads, below a culvert or a point of accidental drainage discharge. In many of these cases, the road itself is on gently sloping, low-hazard terrain, and the landslide occurs on steeper terrain below. This is known as the “gentle-over-steep” situation. The Forest Practices Code does little to reduce landslide hazard in this situation, because the need for professional engineering involvement in road design is triggered by the hazard at the road location, not below the road.

The terrain type most frequently involved in landslides, on an areal basis, is deep glaciofluvial or other stratified glacial deposits in valley bottoms. Otherwise, there are few generalizations that can be made about terrain factors contributing to landslide hazard, or about contributions of landslide sediment to streams. Landslides, like other geomorphic and hydrologic processes, tend to follow magnitude-frequency relations. Small landslides are most frequent, and often do not reach a stream. Large landslides are much less frequent, but often enter streams. In most watersheds, landslides are not a major component of the sediment budget, but in the rare cases where a large landslide occurs, it can dominate the sediment regime for 1 or several years.
INTRODUCTION

A regional study was made of landslides in portions of the Arrow Forest District and the Kootenay Lake Forest District, which permits some preliminary conclusions to be made about the areal frequency of landslides, their causes, and their importance as sediment sources to streams. The main purpose of the study was to determine the terrain attributes most responsible for development-related landslides, and to use this information to improve classification criteria for terrain stability mapping.

The study covered all or parts of 100 map sheets, totalling about one million hectares. Approximately 1700 landslides were inventoried by air-photo interpretation; of these, a subset of about 200 was field checked. These data were supplemented with information on recent landslide events reported to the Engineering Section of the Nelson Forest Region of the B.C. Ministry of Forests.

The landslide inventory includes all landslides visible on air photos, development-related or natural, which are of types commonly caused by forest development. This includes all first-time debris slides, debris avalanches, and debris flows originating from an identifiable source, as well as slumps and rockslides that appear to be first-time events. Not included were chronic or long-lived failures, such as: slump-earthflows, deep-seated bedrock slumps, repeating debris flows that originate in diffuse channel or rockfall sources, chronic rockfall and ravelling on obviously unstable, non-forested slopes, and similar mass movement features.

LANDSLIDE INVENTORY IN ARROW AND KOOTENAY LAKE FOREST DISTRICTS

With the objective of summarizing part of the data that are useful in assessing the risk of landslides affecting populated areas and domestic-use watersheds, a subset of the data was selected, consisting of 24 map sheets centred on the Slocan Valley. This study area totals about 386 000 ha, and includes 582 landslides. Of these, 447, or 77%, are apparently related to development.

Table 1 is a summary of some of the study area statistics, the apparent causes of landslides, and estimated landslide densities. The “apparent cause” is based on air-photo interpretation, and is the apparent primary cause in the opinion of the mapper. These estimates are only an approximation of the actual causes of landslides; causes can be obtained for a small proportion of landslides as derived from engineering reports based on field inspections, and occasionally from field checks done as part of this study. Data on the approximate sizes of the landslides are also included. Considering the distribution of landslides by size classes, it is apparent that the number of landslides in the smallest size class may be underestimated. This is not surprising, as landslides smaller than 0.05 ha are difficult to see on the air photos, and clearly visible evidence of smaller landslides may disappear after a few years.

Our database includes more information on each landslide, including the apparent or known date, slope and aspect, bedrock geology, terrain type
Table 1. Summary of data from landslide inventory, Arrow and Kootenay Lake forest districts

<table>
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<th>Area statistics</th>
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<tr>
<td>Slocan Valley and adjacent sub-areas: 24 map sheets, total area</td>
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<td>Net forested area (excluding parks, alpine areas, farmland, etc.)</td>
<td>298 000 ha</td>
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<td>Area included in development polygons</td>
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<td>Total number of landslides</td>
<td>582</td>
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<tr>
<td>Natural</td>
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<td>Development-related</td>
<td>447</td>
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<tr>
<td>2 (0.05–0.2 ha)</td>
<td>43%</td>
</tr>
<tr>
<td>3 (0.2–1 ha)</td>
<td>30%</td>
</tr>
<tr>
<td>4 (1–5 ha)</td>
<td>2%</td>
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<tr>
<td>5 (&gt; 5 ha)</td>
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<table>
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<tr>
<td>Drainage diversion, road</td>
<td>25%</td>
</tr>
<tr>
<td>Drainage diversion, skid trails</td>
<td>8%</td>
</tr>
<tr>
<td>Road cut</td>
<td>2%</td>
</tr>
<tr>
<td>Clearcut</td>
<td>2%</td>
</tr>
<tr>
<td>Other</td>
<td>4%</td>
</tr>
<tr>
<td>Natural</td>
<td>23%</td>
</tr>
</tbody>
</table>

interpreted from air photos, and type of failure. Further GIS and statistical analyses of the data are in progress.

Although analysis of the data set has not yet been completed, some trends are apparent from the field checking that was done along with terrain mapping in several detailed sub-areas. On older roads, fill failures were the most important cause of landslides. On newer roads, fill failures are uncommon, because under the Forest Practices Code there have been significant improvements to engineering standards aimed at preventing road-fill failures. However, on newer roads, drainage concentration and diversion are the primary causes of landslides. Of the terrain types common in the study area, deep glaciofluvial deposits and other deep stratified glacial (or kame) deposits in valley bottoms appear to be the most susceptible to landslides. There is apparently a greater frequency of landslides from logging on private land than on Crown land. This is due to the widespread use of excavated skid trails on steep slopes, and a lack of drainage control and deactivation on roads and trails; these practices are not allowed on Crown land.

Map 1 shows the study area and the distribution of landslides. It also shows “development polygons,” which consist of logged areas, roads, and all areas below these, down to the nearest water course or valley bottom. In effect, this is the “hydrologic shadow” of roads and cutblocks. This is a more meaningful measure of the area of development than the area of harvesting.
Landslide Inventory
Slocan Valley and adjacent areas

LEGEND
dots: landslides
stippled areas: development polygons
light grey: non-forest areas
dark grey: water bodies
Landslide inventory is current to summer 1999;
development polygons to summer 1998.

MAP 1 Map showing the landslide inventory in the Slocan Valley sub-area. The grid outlines the TRIM 6 x 12' map sheets
would be; relatively few landslides occur in cutblocks, but many occur below cutblocks and roads. The development polygons were identified from a satellite photo, overlain with contours and water courses, using a GIS program (ArcView).

From the data presented in Table 1, some preliminary estimates of areal landslide density can be made. The net forest area is approximately 298,000 ha (excluding alpine areas, parks, water bodies, and urban/agricultural areas). Of this, about 110,000 ha are included in the development polygons. Roughly one-half of the study area is flat or gently sloping land (less than about 30%), and therefore is not subject to landslides. It can be assumed that, very roughly, the total forest land base of steeper land is about 150,000 ha, of which about 50,000 ha are in development polygons. (Stratification of the data by slope classes has not yet been completed.) Assuming that the data set represents landslides that have occurred over a 30-year period, this results in roughly estimated landslide densities of 0.003 natural landslides/km²/y and 0.03 development-related landslides/km²/y. It is noteworthy that almost all (at least 95%) of the development-related landslides are due to roads and skid trails; very few are caused directly by timber harvesting. It can be tentatively concluded that forest development, and in particular roads, increase landslide frequency by a factor of about 10 over natural rates.

These landslide frequencies are much lower than have been reported in terrain attribute studies conducted on the coast. Overall, development-caused landslide frequencies reported by Rollerson and Millard (1998) for study areas on western Vancouver Island and the Queen Charlotte Islands are approximately 0.5 and 1.1 landslides/km²/y, respectively (calculated from the reported frequencies divided by the 15-year time span of the data set). Similar changes in landslide frequency due to forest development have been reported in the coastal studies. For example, in studies on the western Queen Charlotte Islands, post-logging landslide rates were 15 or more times as great as natural rates (Schwab 1998).

An important concept to understand is that landslides, like other geomorphic and hydrologic processes, tend to follow magnitude-frequency relations. Small landslides are most frequent, and often do not reach a stream. Large landslides are much less frequent, but often enter streams. A range of landslide sizes and runout distances is possible, and is often unpredictable at any given site.

In this study, approximately one-tenth of the landslides can be considered “very damaging,” which means that they caused major damage to a stream, or were capable of presenting a risk to downslope inhabited areas. (Most landslides in the inventory were small, or stopped on a forest road, or stopped in timber on the lower slope. Obviously, the judgement of how many landslides are “very damaging” or “significant” is highly subjective.) If one assumes that each of these landslides contributes about 300 t of fine sediment to a stream (again, this is very approximate, but reasonable considering the average size is about 0.2 ha, and the fact that only about one-fifth of the volume of most landslides is fine sediment) then this would amount to an average fine sediment yield of about 1 t/km²/y across the landscape. This is, of course, only an order-of-magnitude estimate. This can be compared to typical, suspended sediment yields, for low geomorphic activity watersheds typically used for community water supply, of about 1–20 t/km²/y (Henderson and Toews, this publication; Jordan, this publication). Development-
related landslides, therefore, appear on average to be a minor but not incon-
sequential component of the sediment budget of creeks in this region.

However, landslides can be a dominant component of the sediment budget
locally and in certain years, as they are a highly episodic process. For example,
in 1996, a large landslide deposited at least 5000 m$^3$ of sediment in Fortynine
Creek, a 25-km$^2$ watershed near Nelson (Figures 5 and 6). If 1000 m$^3$ or 1500 t
of this was suspended sediment deposited in the creek, and if it is assumed
that the background suspended sediment yield was 5 t/km$^2$/y, then this event
would represent about 12 times the typical annual sediment yield. In fact, in
1997, turbidities of 20–3000 NTU were measured during the peak snowmelt
period, due to reworking of slide debris deposited in the channel and erosion
of disturbed banks (no measurements were taken in 1996). In 1996, water
quality was severely affected, and many water intakes were damaged by chan-
nel changes resulting from the influx of coarse sediment. This is an extreme
and unusual example; however, it illustrates how large landslides, if they
occur, can dominate the sediment budget for several years.

“GENTLE-OVER-STEEP” LANDSLIDES

An important category of landslides in our inventory consists of landslides
that occur on steep or potentially unstable slopes, below a point of drainage
discharge on a road on gentler terrain above. These are known locally as
“gentle-over-steep” landslides. Many of the landslides attributed to road
drainage fall in this category. Most often, they occur below a culvert, but also
often occur below a switchback, a cross-ditch, or a point of unintended
drainage diversion. Typically, the failure occurs at a break in slope, where the
slope increases to about 50–70%, often on terrain that would be mapped by
most terrain mappers as Stability Class III. They are equally likely to occur in
forest as in harvested areas. Usually they occur during the snowmelt season,
at a time when the snow line is close to the elevation of the road, and
snowmelt rates are at their maximum (Toews 1991; Jordan and Toews 1993).
Sometimes, the supply of water is enhanced by more rapid snowmelt in
clearcuts above the road. Many of the largest and most mobile landslides in
our data set are of this “gentle-over-steep” category.

The mechanism responsible for “gentle-over-steep” landslides is shown in
the sketches of Figures 1 and 2. In the absence of defined gullies or other sur-
face drainage pathways, water on a hillside tends to move downslope in a
dispersed matter, often as shallow subsurface stormflow through a thin layer
of weathered till or colluvium overlying relatively impermeable, dense,
glacial till or bedrock. When a road is built across the slope, much of this
flow can be intercepted by the road cut and ditch, and carried to cross-drain
culverts. The water is then concentrated in narrow plumes below the cul-
verts. This has two possible effects. One is that if the concentrated flow of
water happens, by chance, to coincide with a location that is less stable than
average—for example, because of locally steeper slopes, thin soil, or conver-
ging subsurface flow paths—and that has not experienced a high flow of water
in the past, then a landslide is likely. The second effect is that the plume of
water can “pre-soak” a long, narrow triangle of soil, raising the pore water
pressure to near-critical values. If something occurs to trigger a small failure
at a point near the top of the plume, then a very large debris avalanche can
occur.
Figure 2 shows in more detail the topographic conditions that favour such landslides. Often, the failure point occurs at a break in slope, where the slope locally increases to some critical value—typically over 60% but occasionally as low as 45%. Often, these steeper slopes are localized, and do not show up on contour maps where the average slope is gentler. Also, at a break in slope, or on a convex slope, the soil depth often decreases downslope, as more rapid soil creep on the steeper slope causes thinning over time. This results in
converging groundwater flow paths, as subsurface flow is squeezed into a narrower layer of soil, and can result in locally greater pore water pressures at the break in slope.

Figure 3 illustrates a typical, although larger-than-average, example of a gentle-over-steep landslide (which occurred outside the study area, southeast of Nelson). Figure 4 shows a location near Slocan where, in May 1990, several landslides and debris flows were triggered below an area where extensive roads and logging covered a gentle plateau above (Curran et al. 1990). The

![Figure 3](image)

**Figure 3** A “gentle-over-steep” landslide, Shaw Creek, Kootenay Lake Forest District. Note road and skid trails above landslide.

![Figure 4](image)

**Figure 4** Cape Horn area, Slocan Lake, Arrow Forest District. In 1990, several landslides and debris flows occurred in the gullies below the logged area.
roads and skid trails had not been deactivated, and some local drainage basins above slide-initiation points had their drainage areas increased by more than double. Several water intakes and private properties, as well as the highway, were damaged by the debris flows. This incident, and several others in the late 1980s (Chow 1988) led to recognition of the “gentle-over-steep” hazard, and also led to significant improvements in road-engineering standards, planning, hazard mapping, and deactivation procedures in the region in the 1990s.

Figures 5 and 6 show the Fortynine Creek landslide of 1996, mentioned above, which seriously affected an important domestic watershed (over 50 water licenses) near Nelson. This landslide occurred below a culvert, which carried an unusually large volume of water, and was probably enhanced by diversion and concentration of water by upslope roads and skid trails. The failure point occurred where the slope steepened to 60% and the soil thinned downslope, as shown in Figure 2. On reaching a steep tributary, the landslide triggered a large debris flow, which continued for 1.2 kilometres until it reached the main creek channel.
A concern regarding risk management of these landslides is that the Forest Practices Code usually does not require professional field assessments of terrain stability, or any special engineering design, when a “gentle-over-steep” situation exists. The need for professional assessments or other measures is triggered by terrain conditions at the site of the road, not on slopes below the road. Therefore, many potentially hazardous situations, where drainage concentrations occur above potentially unstable slopes, go unrecognized.

CONCLUSIONS

Preliminary results of the landslide inventory in Arrow and Kootenay Lake forest districts show that forest development increases landslide frequency, probably in the order of 10 times over natural rates. Landslide frequencies in this region are much lower than those reported in coastal British Columbia. Most landslides in the region are caused by roads. Clearcuts are not an important direct cause of landslides. However, clearcuts sometimes indirectly increase the hazard of landslides caused by drainage concentration, by enhancing snowmelt rates.

Drainage diversion and concentration by roads are the most important causes of landslides on the newer roads. Many landslides are caused by “gentle-over-steep” drainage concentrations; these landslides are significant because they can be very large and can occur on slopes not suspected of being potentially unstable, and because the hazardous situation may go unrecognized, because professional assessments and engineering design are often not required by the Forest Practices Code.

On a watershed scale, the location of roads is clearly an important factor in assessing landslide risk, more so than the rate of cut or the equivalent clearcut area (ECA). In assessing watersheds, either pre-development or for deactivation planning, an important objective should be to identify high-risk roads. These are often roads in low-hazard terrain with higher-hazard slopes below, and not identified as high risk by existing procedures. Planning and assessments should focus on drainage plans for new roads, or deactivation of old roads, in these high-risk locations.

REFERENCES


