
Volume 56, Issues 1–2, March 2007
ISSN 0921-8181
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GLOBAL AND PLANETARY CHANGE
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# Statistical, remote sensing-based approach for estimating the probability of catastrophic drainage from moraine-dammed lakes in southwestern British Columbia

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Received 5 July 2005; accepted 21 July 2006
Available online 14 September 2006

**Abstract**

Safe development of glacierized regions requires a systematic and objective method for assessing the hazard posed by moraine-dammed lakes. Empirical relations exist for estimating outburst flood magnitude, but, until now, no standardized procedures have been developed for estimating outburst flood probability. To make quick and inexpensive preliminary assessments that are reproducible, we propose using a statistical, remote sensing-based approach to estimate the probability of catastrophic drainage of moraine-dammed lakes. We completed a comprehensive inventory of 175 moraine-dammed lakes in the southern Coast Mountains of British Columbia, Canada. By applying logistic regression analysis to the data set, we identified and weighted the following four independent predictor variables that best discriminate *drained* lakes from *undrained* lakes: moraine height-to-width ratio, presence/absence of an ice-core in the moraine, lake area, and main rock type forming the moraine. With an appropriate classification cutoff value, the predictive model correctly classifies 70% of *drained* lakes and 90% of *undrained* lakes, for an overall accuracy of 88%. Our model provides engineers and geoscientists with a tool for making first-order estimates of the probability of catastrophic drainage from moraine-dammed lakes in southwestern British Columbia.


*Keywords:* moraine-dammed lake; outburst flood; hazard; statistical analysis; British Columbia



## 1. Introduction

Moraine-dammed lakes are common in glacierized regions around the world (Lliboutry et al., 1977; Haeberli, 1983; Costa and Schuster, 1988; Clague and Evans, 2000; Richardson and Reynolds, 2000). They form between the snout of a glacier and its own end moraine and, less commonly, on the distal side of moraines where valley drainage has become blocked. Moraine-dammed lakes are prone to catastrophic draining due to the unconsolidated material that constitutes the dams and the steepness of surrounding, commonly avalanche- and rockfall-prone, terrain.

Outburst floods from moraine-dammed lakes have caused tens of millions of dollars of damage to infrastructure and killed thousands of people worldwide (Richardson and Reynolds, 2000). Floodwaters have damaged hydroelectric facilities (Vuichard and Zimmerman, 1987), washed out roads and bridges (Kattelmann,

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doi:10.1016/j.gloplacha.2006.07.004

2003), and destroyed houses and buildings (Huggel et al., 2003).

The hazard posed by moraine-dammed lakes is fundamentally different from most other natural hazards. Whereas the locations of future landslides, earthquakes, and tornadoes, for example, are not known with certainty, the sources of outburst floods from moraine-dammed lakes are readily identified using remote sensing methods. Because the source of the problem is known a priori, engineers and geoscientists have designed a variety of mitigation measures for preventing or reducing the potential size of outburst floods. In some cases, the hazard has been reduced by stabilizing moraine dams and their overflow channels (Lliboutry et al., 1977); in others, lakes have been partially drained (Reynolds et al., 1998). Mitigation, however, is costly, time-consuming, and sometimes unsafe (Lliboutry et al., 1977), thus it is not possible to prevent the sudden failure of all moraine dams. There is interest, therefore, in developing a systematic method for evaluating the risk of moraine dams failing.

Hazard can be broadly defined as the product of magnitude and probability (Fell, 1994). Moraine dam hazard assessments, therefore, must include estimates of both outburst magnitude and outburst probability. Numerous empirical relations have been developed to estimate the probable maximum discharge of outburst floods from moraine-dammed lakes (e.g. Costa and Schuster, 1988; Walder and O'Connor, 1997; Huggel et al., 2002). Peak discharge has a non-linear relation with lake volume, assuming complete drainage, which is "the most appropriate design analysis for planning and possible mitigative measures" (Laenen et al., 1987). Not all outbursts, however, are floods; some transform into debris flows with very different risk implications. Huggel et al. (2004) provide guidelines for estimating the probable maximum volume and travel distance of lake outbursts that transform into debris flows. Although many authors discuss the factors that most likely predispose moraine dams for failure (e.g. Chen et al., 1999; Clague and Evans, 2000; Richardson and Reynolds, 2000; Huggel et al., 2004), no standardized, objective method yet exists for estimating outburst probability.

In an attempt to improve the accuracy of estimates of outburst probability, several authors have specified criteria associated with moraine dam failure. Lu et al. (1987), for example, propose seven numerical "geographic conditions" that favour outburst floods, and both Richardson and Reynolds (2000) and O'Connor et al. (2001) schematically illustrate factors that they link to dam failure. Huggel et al. (2004) list five indicators of a lake's susceptibility to outburst floods, from which they derive a qualitative probability of dam failure.

The purpose of this paper is to provide a more objective approach for estimating outburst flood probability. We use multivariate statistical analysis of remotely measured variables to derive a formula from which the probability of catastrophic drainage from moraine-dammed lakes in the southern Coast Mountains of British Columbia, Canada, can be estimated.

## 2. Basis for a statistical, remote sensing-based approach

A statistical approach for estimating the probability of catastrophic drainage from moraine-dammed lakes was chosen over approaches based on deterministic analysis, return period, and a qualitative geomorphic analysis. Deterministic analysis requires complete understanding of failure mechanisms and prior knowledge of variables, such as the geotechnical properties of the moraine dam, which can only be measured in the field. Moraine dam failure mechanisms are rarely known with certainty (Clague and Evans, 2000; Richardson and Reynolds, 2000), and financial and time constraints preclude regional field investigations.

A return period approach is commonly used in the probabilistic analysis of storm-induced debris flows (Hungr et al., 1984; Jakob and Hungr, 2005). Three factors, however, preclude use of this approach for estimating the probability of outburst floods from moraine-dammed lakes. First, glacial hazards change over time scales shorter than are required to derive frequency relations (Huggel et al., 2004). Second, the dates of past outburst floods are commonly not known with certainty. Third, most moraine-dammed lakes drain only once because the dams are destroyed.

The qualitative geomorphic approach has been used almost exclusively in moraine dam hazard assessments. Richardson and Reynolds (2000) and O'Connor et al. (2001), for example, compare a lake's topographic setting and dam morphology to those of lakes that have drained catastrophically to assess failure susceptibility. Unfortunately, the subjectivity of this approach can result in assessments that are inconsistent, depending on the expertise and biases of the geoscientist.

A superior approach for estimating outburst probability must meet four criteria. First, the approach has to be objective; results of assessments completed by different people are similar. Second, the approach must be simple; hazard evaluation is standardized and follows a specific protocol so that geoscientists without expert knowledge can perform the assessment. Third, the approach should be practical; assessment procedures that minimize the necessary time and cost are preferred by consultants and their clients. Therefore, wherever possible, inexpensive and publicly available data and software are used. Fourth, the approach has to be flexible; the model can be adapted for different data sources, and the conservativeness of the assessment can be adjusted to suit different applications. A statistical, remote sensing-based approach satisfies these four criteria.

The successful application of multivariate statistical analysis of remotely measured parameters in landslide probability studies provides further justification for using a statistical, remote sensing-based approach. Dai and Lee (2003) and Ohlmacher and Davis (2003) used multivariate statistical analysis, in combination with geographic information systems software, to generate landslide probability maps. Their identification of similar predictor variables in different study areas demonstrates that a statistical approach may provide insight into the factors that control a moraine dam's susceptibility to failure. Based, in part, on their studies, the following prerequisites and assumptions should be met to ensure the validity of the model and appropriate interpretation of results: (1) moraine-dammed lakes that have produced an outburst flood (*drained*) can be distinguished from those that have not (*undrained*) with remote sensing methods; (2) lake parameters can be accurately measured; (3) sampled lakes represent all variability in the study area; (4) the same mechanisms that were responsible for past moraine dam failures will cause future failures; and (5) the sample size is large enough for statistical analysis.

Given these prerequisites and assumptions, a statistical model for estimating the probability of catastrophic drainage from moraine-dammed lakes in southwestern British Columbia cannot be based solely on the nine instances of moraine dam failure documented in the literature (Blown and Church, 1985; Clague et al., 1985; Evans, 1987; Ryder, 1991; Clague and Mathews, 1992; Clague and Evans, 2000; Kershaw et al., 2005). The sample size could be increased by including dam failures in other glacierized regions such as the Himalayas, Andes, or Alps. However, basing a statistical model on possibly morphologically distinct moraine dams in different mountain ranges, although increasing the

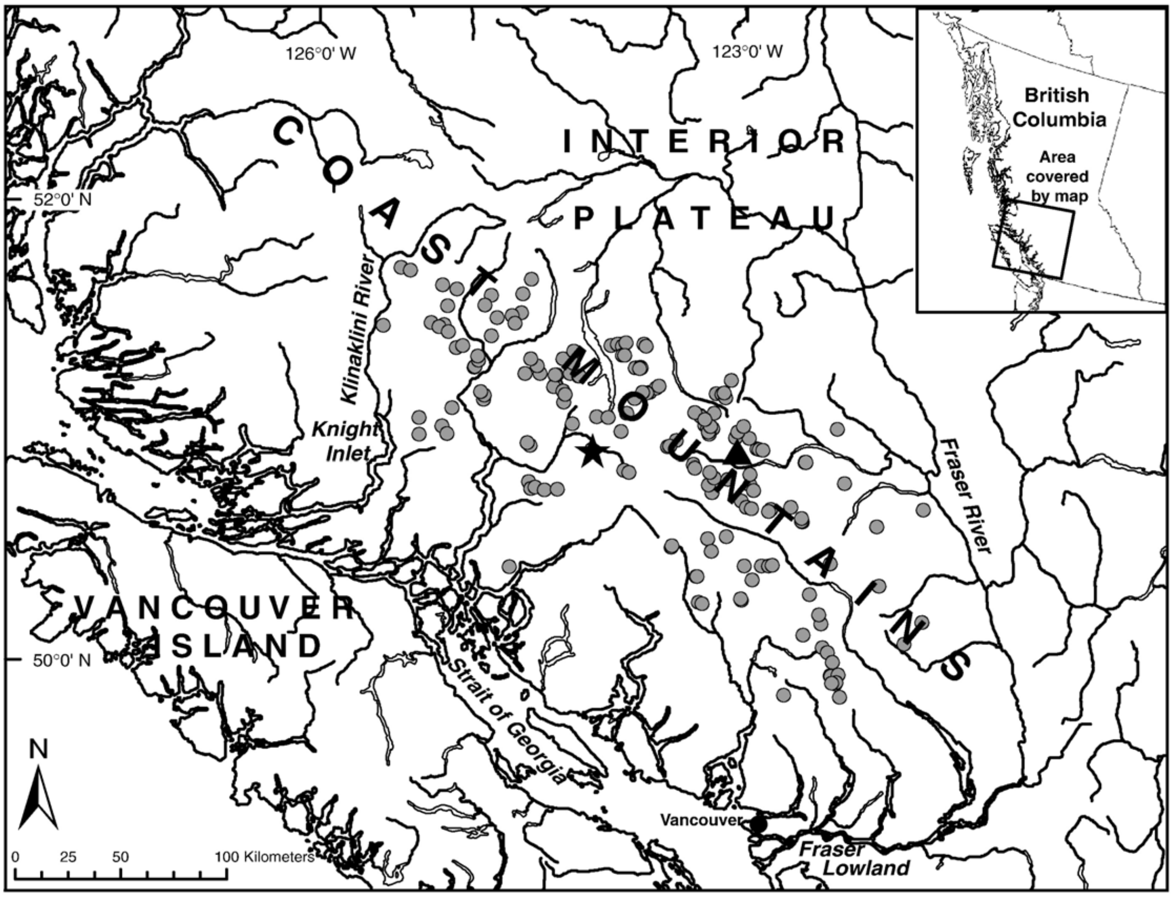


Fig. 1. Study area showing locations of 175 moraine-dammed lakes larger than 1 ha. Unnamed moraine-dammed lakes above the Gilbert Glacier (black star, see Fig. 8) and west of Scherle Peak (black triangle, see Fig. 9) are used to demonstrate the application of the predictive model.

Table 1
Candidate predictor variables

| No.[a] | Variable | Code | Data source[b] | Data type[c] | Units[d] | Definition | Reference[e] |
|---|---|---|---|---|---|---|---|
| 1 | Lake freeboard | Freebrd | AP | C | m | Elevation difference between lake surface and lowest point in moraine crest | Blown and Church (1985) |
| 2 | Lake freeboard-to-moraine crest height ratio | Frb_M_ht | AP | C | – | Ratio between lake freeboard (#1) and moraine crest height (elevation difference between toe and crest of moraine dam) | Huggel et al. (2004) |
| 3 | Lake area | Lk_area | TRIM | C | ha | Lake surface area | Chen et al. (1999) |
| 4 | Moraine height-to-width ratio | M_hw | AP | C | – | Ratio between moraine height (elevation difference between lake surface and toe of moraine dam) and moraine width (horizontal distance between distal lakeshore and toe of moraine dam) | Clague and Evans (2000), Huggel et al. (2002) |
| 5 | Moraine distal flank steepness | M_d_flnk | AP | C | ° | Slope from crest to toe of moraine dam | Chen et al. (1999) |
| 6 | Moraine vegetation coverage | M_veg | AP | N | – | Density of vegetation (grass, shrubs, trees) on moraine dam— contiguous or discontiguous | Costa and Schuster (1988), Goldsmith (1998) |
| 7 | Ice-cored moraine | Ice_core | M and AP | N | – | Moraine dam type— ice-cored or ice-free | Kattelmann (2003) |
| 8 | Main rock type forming moraine | Geology | BCGS | N | – | Bedrock lithology surrounding and/or upstream of lake— granitic, volcanic, sedimentary, metamorphic | Blown and Church (1985); this study |
| 9 | Lake–glacier proximity (horizontal distance) | Lk_gl_prx | AP | C | m | Horizontal distance between glacier snout and nearest lakeshore | Ding and Liu (1992), Chen et al. (1999) |
| 10 | Lake–glacier relief (vertical distance) | Rlf_glac | AP | C | m | Elevation difference between lake surface and glacier snout | Singerland and Voight (1982) |
| 11 | Slope between lake and glacier snout | Lk_gl_slp | AP | C | ° | Slope from glacier snout to nearest lakeshore | Ding and Liu (1992) |
| 12 | Crevassed glacier snout | Crevasse | AP | N | – | Lowermost 500 m of glacier— crevassed or crevasse-free | Ding and Liu (1992) |
| 13 | Glacier calving front width | Calve | AP | C | m | Horizontal distance between left and right margin of calving glacier | Lliboutry et al. (1977), Richardson and Reynolds (2000) |
| 14 | Glacier snout steepness | Snout_st | TRIM | C | ° | Slope of lowermost 500 m of glacier | Alean (1985) |
| 15 | Snow avalanches enter lake | Snow_av | AP | N | – | Evidence of snow avalanches entering lake (remnant avalanche debris, vegetation trimlines, or avalanche gully at lakeshore)— yes or no | Ryder (1998) |
| 16 | Landslides enter lake | Landsld | AP | N | – | Evidence of landslides entering lake (coherent deposit of landslide debris)— yes or no | Evans (1987), Ryder (1998) |
| 17 | Unstable lake upstream | Us_lk | AP | N | – | Upstream ice-dammed lake, moraine-dammed lake, landslide-dammed lake, or bedrock-dammed lake situated beneath hanging glacier— yes or no | Huggel et al. (2003) |
| 18 | Watershed area | Watershd | TRIM | C | ha | Watershed area above lake outlet | Clague and Evans (1994) |

Measurements for drained lakes based on observations from pre-outburst data sources or on reconstruction of pre-outburst conditions.
[a] See Fig. 3 for schematic definition of predictor variables.
[b] AP = aerial photographs; TRIM = online 1:20 000-scale Terrain Resource Information Management topographic maps; BCGS = online British Columbia Geological Survey geological maps; M = 1:2 000 000-scale moraine type map (Ostrem and Arnold, 1970).
[c] C = continuous; N = nominal.
[d] m = metres; ha = hectares (1 ha = 10 000 $m^2$); ° = degrees; – = unitless.
[e] Authors either directly cite variable as an important predictor of outburst probability or provide basis for its inclusion.



model's spatial applicability, would likely compromise its predictive capability within southwestern British Columbia. The lack of consistency of morphological data published in the literature further limits the use of existing data, at least without rigorous data homogenization. Furthermore, few quantitative data have been published on *undrained* moraine-dammed lakes. A statistical model cannot reliably identify lakes that are likely to drain catastrophically if it is based entirely on data collected from *drained* lakes.

## 3. Study area

We completed a comprehensive inventory of all drained and undrained moraine-dammed lakes larger than one hectare in British Columbia's southern Coast Mountains (Fig. 1). We used a lake area threshold of one hectare because outburst floods from lakes of this size have considerable destructive potential (e.g. Tats Lake, Clague and Evans, 1992) and can be reliably detected on medium-scale aerial photographs. The study area is 70 000 km$^2$ in size and is bounded on the south by the Strait of Georgia and Fraser Lowland, on the west by Knight Inlet and Klinaklini River, on the north by the Interior Plateau, and on the east by Fraser River. The Coast Mountains extend from the International Boundary about 1700 km northwest to Alaska and Yukon. The Coast Mountains are composed mainly of Late Jurassic to Early Tertiary granitic rocks, intermediate- to high-grade metamorphic rocks, and minor Cenozoic volcanic rocks (Monger and Journeay, 1994).

Elevations in the southern Coast Mountains range from sea level in coastal fjords to over 4000 m at the summit of Mount Waddington. Local relief is typically between 1000 and 2000 m. The high relief and rugged topography are largely the product of late Tertiary and Quaternary tectonic uplift and coupled fluvial and glacial erosion (Parrish, 1983; Mathews, 1989). Many valleys have broad bottoms and steep sides, and contain thick Quaternary sediments. Contemporary glaciers range in size from small cirque glaciers to icefields up to 400 km$^2$ in area straddling the drainage divide of the Coast Mountains. Conspicuous late Holocene moraines, mostly deposited during the Little Ice Age (Matthes, 1939; Grove, 1988), occur near the margins of many glaciers throughout the study area. The moraines average about 30 m high, but some exceed 100 m in height. They are composed of unconsolidated diamicton and very poorly sorted bouldery gravel. The moraine matrix is dominantly sand, but includes significant finer material.

Synoptic-scale climate ranges from wet maritime on the coast and windward western slopes to drier sub-maritime in the rain shadow of the Coast Mountains. Climate is orographically modified in alpine and sub-alpine regions where most moraine-dammed lakes are located. Mean annual precipitation on the lee side of the range is less than 500 mm, whereas the windward slopes and major icefields receive more than 3000 mm annually (Canadian National Committee for the International Hydrological Decade, 1978). Precipitation is generally heaviest in the late autumn when Pacific cyclones move onto the British Columbia coast. Flooding occurs in small to intermediate-size watersheds during intense rain-on-snow events in autumn and during early summer freshet in large drainage basins such as that of Fraser River.

## 4. Database development

Moraine-dammed lakes were detected and measurements were made using aerial photographs (Table 1). Huggel et al. (2002) developed GIS-based algorithms for

Table 2
Comparison of aerial photograph-based photogrammetric measurements with field-based measurements

| Lake | Location | | Terrain feature | Distance measure | Measurement (m) | | |
|---|---|---|---|---|---|---|---|
| | Longitude (W) | Latitude (N) | | | Photogrammetric | Field | Percent error (%)[a] |
| Queen Bess | 124° 30′ 52″ | 51° 15′ 12″ | Narrow terminal moraine width | Horizontal | 54 | 55 | 2 |
| East Granite | 123° 20′ 49″ | 51° 3′ 30″ | Debris fan width | Horizontal | 64 | 60 | 7 |
| Boomerang | 123° 9′ 10″ | 51° 38′ 42″ | Moraine width | Horizontal | 296 | 300 | 1 |
| Soo Lower | 123° 12′ 57″ | 50° 14′ 51″ | Lake outlet to tributary lake outlet | Horizontal | 511 | 500 | 2 |
| Salal | 123° 24′ 5″ | 50° 44′ 55″ | Lakeshore to lateral moraine crest | Horizontal | 111 | 120 | 8 |
| Nichols | 123° 23′ 12″ | 50° 58′ 2″ | Lake length | Horizontal | 176 | 185 | 5 |
| Nichols | 123° 23′ 12″ | 50° 58′ 2″ | Moraine width | Horizontal | 88 | 90 | 2 |
| Nichols | 123° 23′ 12″ | 50° 58′ 2″ | Nearby lake length | Horizontal | 44 | 47 | 6 |
| Queen Bess | 124° 30′ 52″ | 51° 15′ 12″ | Lake surface to moraine crest | Vertical | 48 | 50 | 4 |
| Queen Bess | 124° 30′ 52″ | 51° 15′ 12″ | Freeboard of pond in lateral moraine | Vertical | 4 | 5 | 20 |
| Queen Bess | 124° 30′ 52″ | 51° 15′ 12″ | Freeboard of pond in terminal moraine | Vertical | 2 | 5 | 60 |
| East Granite | 123° 20′ 49″ | 51° 3′ 30″ | Moraine breach height | Vertical | 18 | 21 | 14 |
| Soo Lower | 123° 12′ 57″ | 50° 14′ 51″ | Moraine breach height | Vertical | 22 | 30 | 27 |
| Salal | 123° 24′ 5″ | 50° 44′ 55″ | Lake surface to moraine crest | Vertical | 11 | 10 | 10 |
| Nichols | 123° 23′ 12″ | 50° 58′ 2″ | Moraine height | Vertical | 7 | 6 | 17 |
| Nichols | 123° 23′ 12″ | 50° 58′ 2″ | Moraine height | Vertical | 33 | 35 | 6 |

[a] Percent error = [|photogrammetric measurement − field measurement| / field measurement] * 100%.

detecting glacial lakes using Landsat satellite imagery, which may be the more economical solution for study regions where recent aerial photograph coverage is incomplete, but we used aerial photographs for four reasons: (1) they have higher spatial resolution than satellite images, which is sometimes needed to distinguish moraine- and bedrock-dammed lakes; (2) they are inexpensive, provide complete recent coverage of our study area, and can be viewed for free at provincial and federal aerial photograph libraries in Canada; (3) vertical relief and horizontal distances can be measured on aerial photographs; and (4) they are routinely used by geoscientists and engineers in hazard assessments. We used, where possible, 1:30 000- to 1:40 000-scale, post-1990 aerial photographs for lake detection, and 1:15 000-scale photographs for measurements. All photogrammetric measurements were made using a mirror stereoscope and parallax bar, following techniques outlined by Lillesand and Kiefer (2000). By computing the magnitude of relief displacement on a point-by-point basis, it was possible to plot features in their planimetrically correct positions and thereby accurately measure horizontal distances (Table 2). The relief displacement of features such as moraine dams enabled heights to be determined using standard photogrammetric methods (Table 2). Lillesand and Kiefer (2000), however, point out five assumptions implicit in the use of the method: (1) aerial photographs are truly vertical; (2) flying height is accurately known; (3) objects are clearly visible; (4) principal points are precisely located on the photographs; and (5) the measurement technique used has an accuracy that is consistent with the degree of relief displacement involved. To increase the precision and consistency of photogrammetric measurements, all parallax bar readings were repeated until three consecutive readings were within 0.05 mm of each other, which corresponds to a ground feature height uncertainty of about 2–3 m on 1:15 000-scale photographs.

We also examined maps. Measurements of lake area and watershed area were made from online 1:20 000-scale Terrain Resource Information Management (TRIM) topographic maps (Table 1). Although measurable through photogrammetric methods, glacier snout steepness was also measured from TRIM maps because only an average gradient over the lowermost 500 m of the glacier was required. To verify that using photogrammetric measurements for such a coarse measurement is unnecessary, we changed a random selection of glacier snout steepness values by 50% and re-ran the statistical analysis. Because no major systematic differences in glacier snout steepness were observed between drained and undrained lakes, the changes had no effect on the final model. The main rock type forming each moraine dam, which we assumed to be the same as the local bedrock, was determined from online British Columbia Geological Survey (BCGS) geological maps (Table 1). Moraine dam type for about half of the lakes in the study area is based on Ostrem and Arnold's (1970) 1:2 000 000-scale map of ice-cored and ice-free moraines in southern British Columbia. For moraine dams that are not shown on Ostrem and Arnold's map, we based our assignment on a combination of several criteria they outline for distinguishing ice-cored from ice-free moraines using aerial

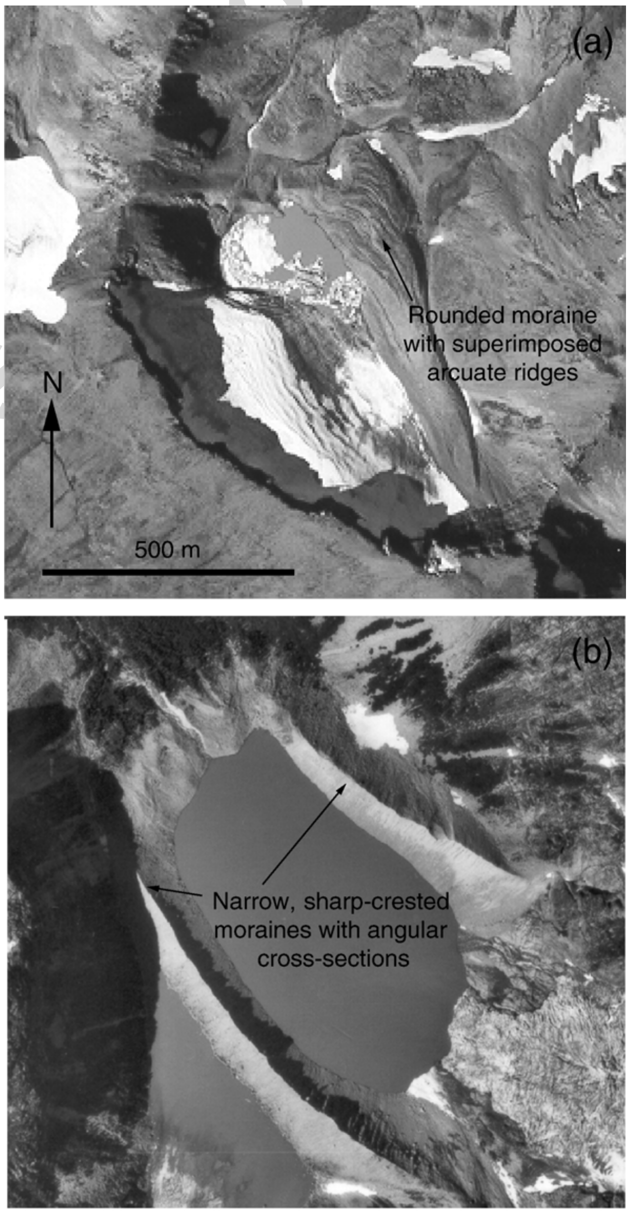


Fig. 2. Typical (a) ice-cored and (b) ice-free moraine dams in the southern Coast Mountains. Aerial photographs (a— 30BCC97175-156; b— 30BC79069-190) reproduced with permission of the Province of British Columbia.

photograph interpretation: (1) a moraine with a rounded surface with minor superimposed ridges was assumed to be ice-cored; (2) a disproportionately large end moraine in front of a small glacier was suspected to be ice-cored; and (3) a narrow, sharp-crested moraine with an angular cross-section was interpreted to be ice-free (Fig. 2). Through ground truthing for a similar study in Scandinavia, Ostrem (1964) found the assumptions concerning the presence or absence of an ice-core "could generally be confirmed." Because very few moraine dams in Ostrem's (1964) study were misclassified using the criteria outlined above, we suspect a similarly small number of moraine dams in our study area were misclassified. However, to test the effect of misclassification of moraine type, we re-ran the statistical analysis after switching the moraine types of a random selection of 5% of the moraine dams. The main results of the statistical analysis did not change.

We conducted limited field investigations in the summer of 2004 to verify the aerial photograph observations and measurements, to assess changes in some lake–glacier systems since the aerial photographs were taken, and to make first-hand observations to better understand what conditions may predispose a moraine dam to fail. We visited 25 drained and undrained lakes, ranging in size from 1 ha to about 200 ha. Financial constraints and the remoteness of most lakes precluded detailed surveys of lake bathymetry and moraine dam morphology, thus the focus in the field was to ground truth remote measurements. Samples of moraine dam matrix (<2 mm) were collected at about 20 sites to characterize the material properties of moraines in the study area.

We identified 175 moraine-dammed lakes in the study area. Only 11 of the 175 lakes had drained or partially drained. Event occurrences (in this case drained lakes) are statistically more informative than non-occurrences (undrained lakes) (King and Zeng, 2001), thus the predictive capability of our statistical model

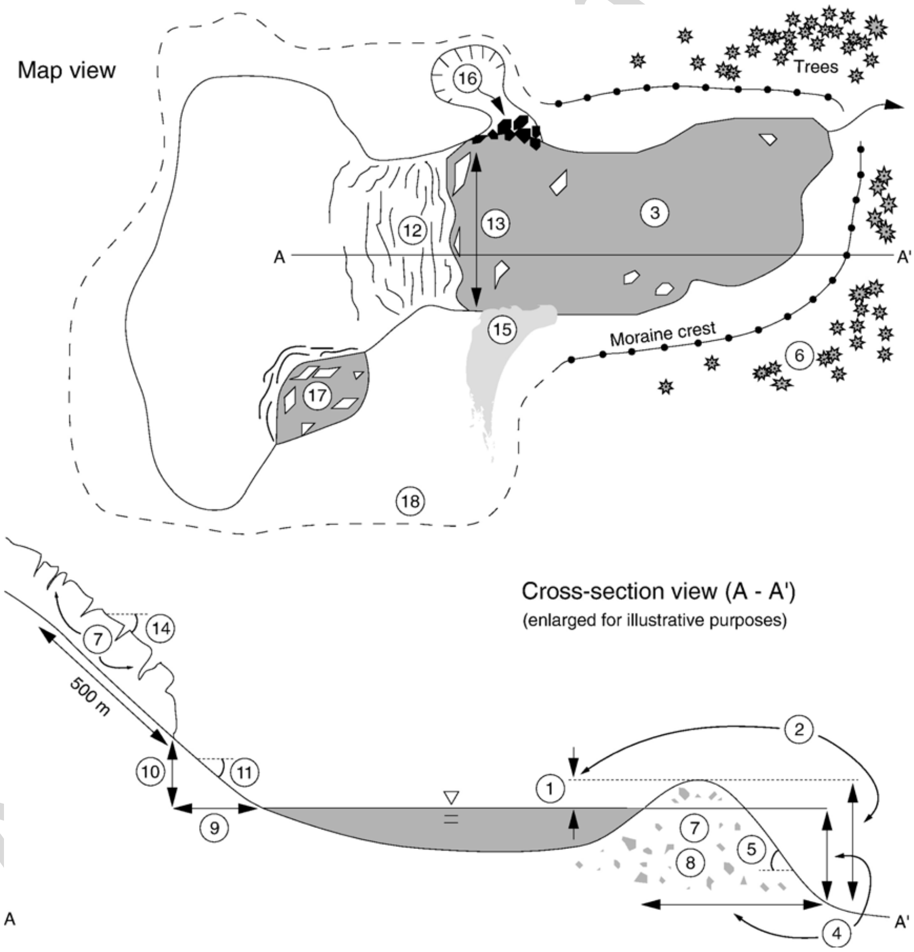


Fig. 3. Eighteen candidate predictor variables. Numbers are cross-referenced to those in Table 1: (1) lake freeboard, (2) lake freeboard-to-moraine crest height ratio, (3) lake area, (4) moraine height-to-width ratio, (5) moraine distal flank steepness, (6) moraine vegetation coverage, (7) ice-cored moraine, (8) main rock type forming moraine, (9) lake–glacier proximity (horizontal distance), (10) lake–glacier relief (vertical distance), (11) slope between lake and glacier, (12) crevassed glacier snout, (13) glacier calving front width, (14) glacier snout steepness, (15) snow avalanches enter lake, (16) landslides enter lake, (17) unstable lake upstream, and (18) watershed area.

Table 3
Wald tests of the significance of predictor variables in the outburst probability model

| Variable | Order of stepwise entry | Degrees of freedom | Wald chi-square | Prob > chi-square |
|---|---|---|---|---|
| M_hw | 1 | 1 | 17.3386 | <0.0001 |
| Ice_core | 2 | 1 | 4.7117 | 0.0300 |
| Lk_area | 3 | 1 | 4.6977 | 0.0302 |
| Geology | 4 | 3 | 9.2515 | 0.0261 |

would be compromised unless we could increase the number of drained lakes in our database. To address this problem, we could have expanded our study area until we had identified enough drained lakes to validate the statistical analysis. However, to increase the number of drained lakes to 20 would require roughly doubling the study area, which was not feasible. Time and financial constraints forced us, instead, to supplement our database with drained lakes from outside the initial study area, but still within the Pacific Northwest. We added five drained lakes from British Columbia and four drained lakes and one undrained lake from Washington and Oregon. Qualitative and quantitative measurements for the 20 drained lakes and 166 undrained lakes provided the data set for statistical analysis.

## 5. Candidate predictor variables

We chose candidate predictor variables on the basis of previously published accounts of moraine dam failures and field observations. Variables were only included if they met three criteria. First, variable measurement had to be objective. Repeat measurements should be consistent, and different analysts should obtain similar results. Second, only variables for which a physical basis for inclusion could be hypothesized were included. Third, variables could be measured on aerial photographs or maps. Our philosophy of developing a method for making quick and inexpensive preliminary assessments of moraine-dammed lake outburst probability,

Table 4
Regression coefficients estimated for the outburst probability model

| Variable | Category | Coefficient |
|---|---|---|
| Intercept | – | −7.1074 (α) |
| M_hw | – | 9.4581 ($\beta_1$) |
| Ice_core$_j$: | Ice-free | 1.2321 ($\beta_{\text{Ice-free}}$) |
| | Ice-cored | −1.2321 ($\beta_{\text{Ice-cored}}$) |
| Lk_area | – | 0.0159 ($\beta_2$) |
| Geology$_k$: | Granitic | 1.5764 ($\beta_{\text{Intrusive}}$) |
| | Volcanic | 3.1461 ($\beta_{\text{Volcanic}}$) |
| | Sedimentary | 3.7742 ($\beta_{\text{Sedimentary}}$) |
| | Metamorphic | −8.4968 ($\beta_{\text{Metamorphic}}$) |

therefore, precluded variables that could only be measured through field work.

Fortunately, few potentially important predictor variables had to be excluded because they could only be measured on-site. Lake bathymetry, which influences lake volume, dam hydraulic conditions, and displacement wave propagation and run-up (Kershaw et al., 2005), requires field surveys and thus was excluded. Geotechnical characteristics of the moraine dam, which may affect its resistance to erosion during anomalous overflow events, obviously could not be assessed without field sampling and subsequent laboratory analysis. Seepage through the moraine dam, which can initiate piping failure (Lliboutry et al., 1977; Huggel et al., 2003), could not reliably be observed on aerial photographs.

We also excluded remotely measurable variables that are either spatially homogeneous within the study area or are difficult to objectively quantify. The seismicity of a region, for example, would intuitively be included as a candidate predictor variable. An earthquake can destabilize a moraine dam (Lliboutry et al., 1977) or trigger an ice avalanche or rockfall that may enter the lake and generate displacement waves capable of overtopping the dam. Seismicity, however, differs little throughout our study area (Anglin et al., 1990) and therefore was excluded from the list of candidate predictor variables. Huggel et al. (2004) include the local frequency of "extreme meteorological events" (high temperature and precipitation) as a predictor variable in their subjective scheme for estimating a "qualitative probability" of outburst. Storm- and snowmelt-induced runoff have been cited by several authors as a trigger mechanism for moraine dam failure (e.g. Lliboutry et al., 1977; Yamada, 1998). Unfortunately, however, isohyet maps of short-duration, intense rainstorms, which provide the best spatial quantification of "extreme meteorological events," are unavailable for moraine dams in British Columbia due to the scarcity of climate stations capable of measuring continuous rainfall (Canadian National Committee for the International Hydrological Decade, 1978).

After excluding predictor variables that require field measurement and those that are spatially homogeneous

Table 5
Maximum negative log-likelihood values for testing the significance of outburst probability models

| Whole model test | | | | |
|---|---|---|---|---|
| Model | Log-likelihood | Degrees of freedom | Chi-square | Prob > chi-square |
| Difference | 19.6529 | 6 | 39.3059 | <0.0001 |
| Fitted | 43.8313 | | | |
| Reduced (intercept-only) | 63.4843 | | | |

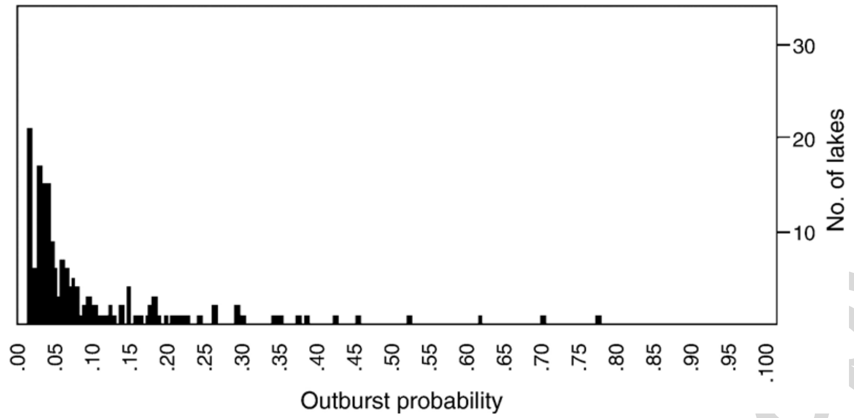


Fig. 4. Histogram showing the distribution of outburst probability estimates derived from the logistic regression model.

or difficult to objectively quantify, the number of candidate predictor variables was reduced to 18 (Table 1). Fig. 3 provides a schematic definition of the 18 predictor variables. Three of the variables are related to the lake, five to the moraine dam, six to the glacier, and four to the basin. The candidate predictor variables include both continuous and nominal types of data (Table 1).

## 6. Development of the predictive model

The number of possible multivariate statistical procedures that can be applied to our data set is limited by the type and distributional form of the data. The simplest statistical prediction method uses contingency table analysis, in which the discrete categories of one or more predictor variables are cross-tabulated with each state of the dichotomous dependent variable (Ohlmacher and Davis, 2003). The proportion of tallies in each cell of the table can be interpreted as conditional outburst probabilities, given a state of the predictor variable. Unfortunately, the relatively large number of predictor variables in this study makes contingency table analysis unwieldy.

Discriminant analysis classifies individuals into mutually exclusive groups on the basis of a set of independent variables (Dillon and Goldstein, 1984). Linear combinations of the independent variables are derived that will discriminate between groups by maximizing between group variance and simultaneously minimizing within-group variance. Press and Wilson (1978) strongly discourage using discriminant analysis in situations, such as in this study, where at least one independent variable is nominal, thereby violating the assumption of multivariate normality.

Linear regression is perhaps the most commonly used method for predicting the value of a dependent variable from observed values of a set of predictor variables (Dillon and Goldstein, 1984). Although the method can be generalized to include nominal predictor variables, linear regression requires that the dependent variable be normally distributed (continuous). In situations such as this study, where the dependent variable is dichotomous and the predictor variables are either continuous (e.g. moraine height-to-width ratio) or nominal (e.g. main rock type forming the moraine), the most appropriate multivariate statistical method is logistic regression.

Logistic regression is an extension of linear regression, developed for situations in which the dependent variable is dichotomous rather than continuous. In linear regression, we estimate or predict the mean value of the response corresponding to a particular set of values for the

Table 6
Cross-validation of logistic regression model based on (a) a default 50% probability cutoff and (b) a 19% probability cutoff

(a) 50% probability cutoff

| | | Observations | | Total |
|---|---|---|---|---|
| | | 0 (*undrained*) | 1 (*drained*) | |
| Predictions | 0 (*undrained*) | 164 | 12 | 176 |
| | | 99% | 60% | |
| | 1 (*drained*) | 2 | 8 | 10 |
| | | 1% | 40% | |
| Total | | 166 | 20 | 186 |

(b) 19% probability cutoff

| | | Observations | | Total |
|---|---|---|---|---|
| | | 0 (*undrained*) | 1 (*drained*) | |
| Predictions | 0 (*undrained*) | 150 | 6 | 156 |
| | | 90% | 30% | |
| | 1 (*drained*) | 16 | 14 | 30 |
| | | 10% | 70% | |
| Total | | 166 | 20 | 186 |

Notes: Probability cutoff is the threshold above which lakes are classified as *drained* and below which lakes are classified as *undrained*. Model specificity and sensitivity are 99% and 40%, respectively, for (a) and 90% and 70%, respectively for (b).

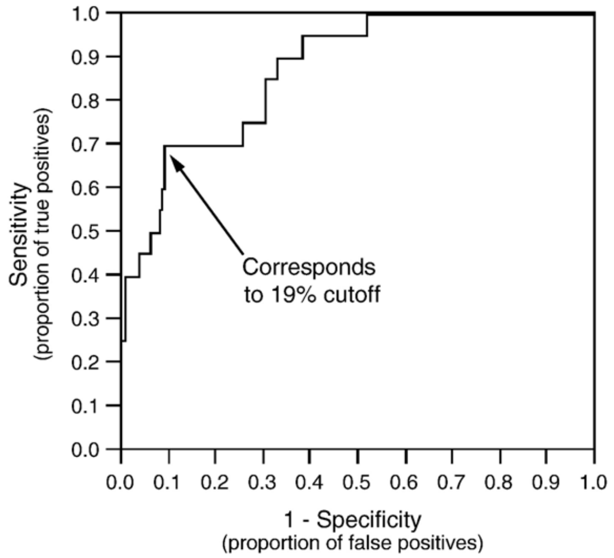


Fig. 5. ROC curve for logistic regression model (see text for explanation). The point closest to the upper-left corner of the diagram corresponds to a probability threshold of 19%. The area under the ROC curve is 0.869.

predictor variables (Pagano and Gauvreau, 2000). In our situation, where the response is dichotomous, we are interested in estimating the probability that a lake will be classified into one category as opposed to another, given a particular set of predictor variables. Each lake can be represented by a dichotomous variable, $Y$, which indicates whether a lake is drained ($Y=1$) or undrained ($Y=0$), and $n$ independent variables, $X_1, X_2, \ldots, X_n$. Because $Y$ is dichotomous, the probability that $Y=1$ is also the expected value of $Y$, given $X_1, X_2, \ldots, X_n$; that is, $P(Y=1)$ is the regression against $X_1, X_2, \ldots, X_n$ (Dai and Lee, 2003). By definition, $P(Y=1)$ is restricted to values between zero and one, and, because dichotomous categories are mutually exclusive, $P(Y=0)=1-P(Y=1)$.

We wish to estimate $P(Y=1)$, given a set of independent variables. Therefore, we initially attempt to directly model $P(Y=1)$ by regression:

$$P(Y=1)=\alpha+\beta_1X_1+\beta_2X_2+\ldots+\beta_nx_n, \tag{1}$$

where $\alpha$ is the intercept and $\beta_i$ are the regression coefficients estimated from the data. Such a model, however, can yield both positive and negative values outside the probability limits. We can partly circumvent this problem by regression modelling of the odds, which are defined as the ratio of the probability that something occurs to the probability that it does not occur:

$$\begin{aligned}\text{Odds}(Y=1)&=P(Y=1)/[1-P(Y=1)]\\&=\alpha+\beta_1X_1+\beta_2X_2+\ldots+\beta_nX_n\end{aligned} \tag{2}$$

The odds are a ratio with no fixed maximum, but we are left with the problem that the odds have a minimum value of zero. In order to eliminate this final problem, we take the natural logarithm of the odds, called the logit of $Y$, thereby producing a variable that has no numerical limits:

$$\begin{aligned}\text{logit}(Y)&=\ln\{P(Y=1)/[1-P(Y=1)]\}\\&=\alpha+\beta_1X_1+\beta_2X_2+\ldots+\beta_nX_n\end{aligned} \tag{3}$$

Logit($Y$) approaches negative infinity as the odds decrease from one to zero, and positive infinity as the odds become increasingly larger than one. Although the

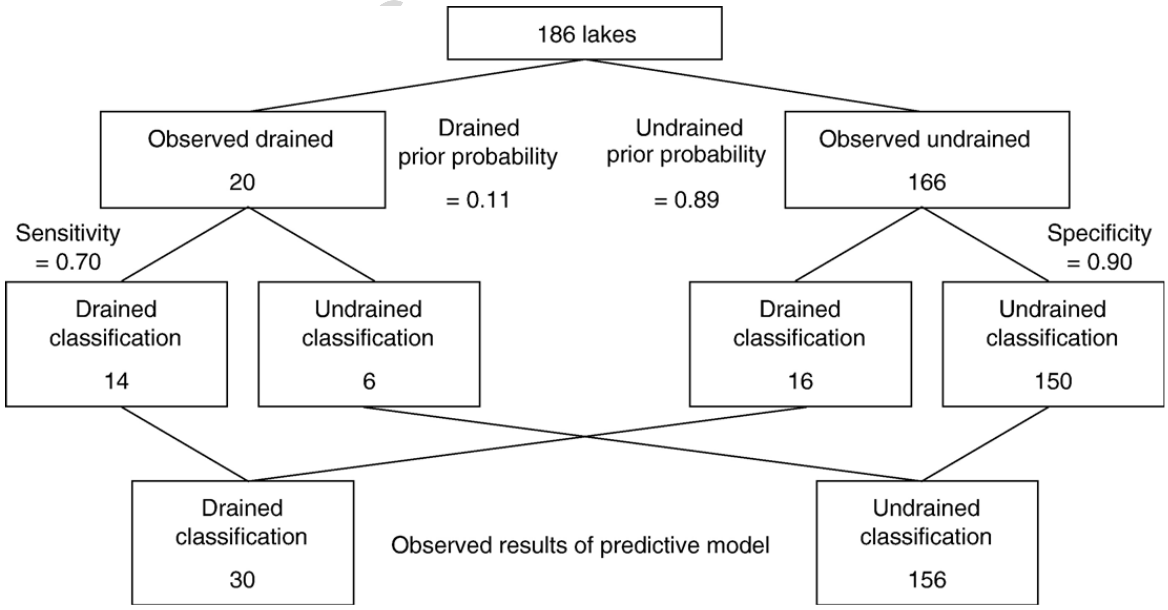


Fig. 6. Schematic representation of the performance of the logistic regression model as a predictor of outburst probability (based on Pagano and Gauvreau, 2000, Fig. 6.3).

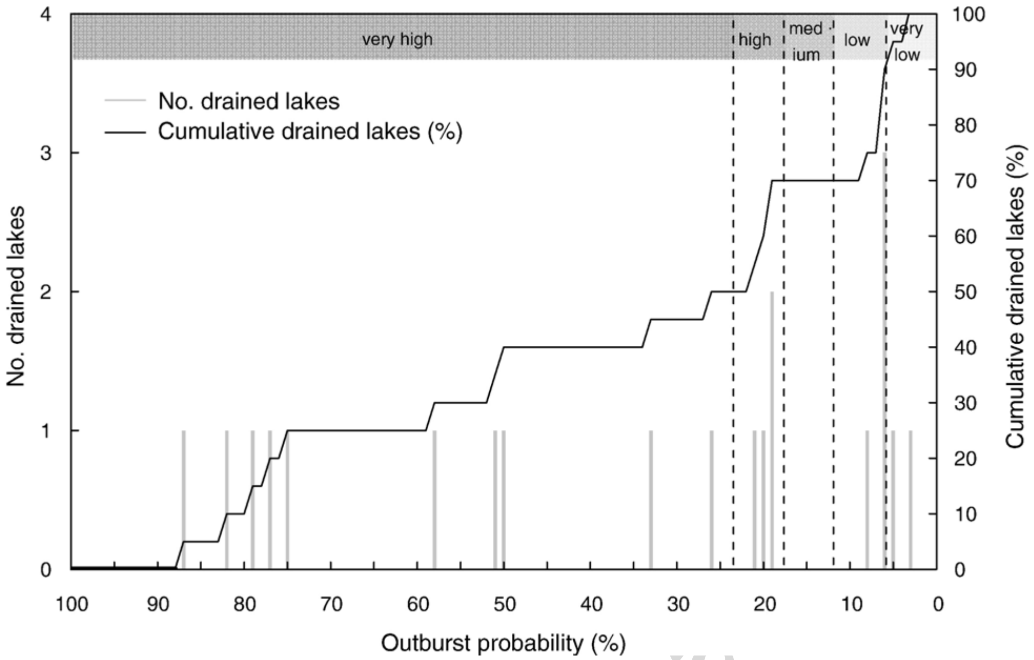


Fig. 7. Distribution of outburst probability estimates for drained lakes in the statistical database. The black curve is the cumulative percentage of drained lakes based on outburst probability estimates. Breaks in the slope of this curve, for example at 6%, provide an objective basis for defining probability categories (top of graph).

probability, the odds, and the logit are three ways of expressing the same thing, the logits have no constraints that would otherwise make it impossible to use regression in a predictive model (Ohlmacher and Davis, 2003).

By converting logit($Y$) back to the odds and then the odds back to $P(Y=1)$, we derive the logistic regression equation: $P(Y=1)=\exp(\alpha+\beta_1X_1+\beta_2X_2+\ldots+\beta_nx_n)/[1+\exp(\alpha+\beta_1X_1+\beta_2X_2+\ldots+\beta_nx_n)]$. Further simplification produces a succinct expression from which moraine-dammed lake outburst probability can be estimated in terms of the variables $X_1, X_2, \ldots, X_n$:

$$P(Y=1)=\{1+\exp[-(\alpha+\beta_1X_1+\beta_2X_2+\ldots+\beta_nX_n)]\}^{-1} \tag{4}$$

Linear regression coefficients are estimated using ordinary least squares, whereas logistic regression coefficients are estimated using the maximum likelihood method. Maximum likelihood estimation, in a general sense, yields values for the unknown coefficients that maximize the probability of obtaining the observed set of data (Hosmer and Lemeshow, 2000). Because the relation between the independent predictor variables and outburst probability is non-linear, logistic regression software uses iterative methods to estimate coefficients.

The relative performance of different logistic regression models can be evaluated using a test statistic called the negative log-likelihood, which has approximately a chi-square distribution (Ohlmacher and Davis, 2003). The negative log-likelihood of the reduced (intercept-only) model is compared to that of the fitted model. If the difference between the negative log-likelihood of each model passes a chi-square test of significance, the fitted model better describes the data than the reduced model. The output from logistic regression software closely resembles analysis of variance tables used to test linear regression coefficients, except that the test statistic follows a chi-square distribution rather than an $F$ distribution (Ohlmacher and Davis, 2003).

We performed logistic regression with the software JMP v. 5 (SAS Institute Inc., 2003). We selected variables using a forward stepwise procedure to ensure that we generated the most parsimonious model and to reduce the chance that two strongly correlated variables were entered into the model (Quinn and Keough, 2002). In a forward stepwise procedure, variables are entered into the model one at a time, beginning with the statistically most important. After each step, the model is re-evaluated to determine whether additional variables should be entered. The re-evaluation is done by comparing the negative log-likelihood of the model before and after the addition of each variable (Dai and Lee, 2003). For this study, a variable under consideration was only entered into the model if the significance was less than a “probability to enter” of 0.05. The process continued until further addition of variables did not significantly improve the model's predictive capability.

## 7. Modelling results

According to the forward stepwise logistic regression, moraine-dammed lake outburst probability in southwestern British Columbia is best predicted by four variables (Tables 3 and 4). In order of their entry into the model, the variables are moraine height-to-width ratio (M_hw), presence/absence of an ice-core in the moraine (Ice_core), lake area (Lk_area), and main rock type forming the moraine (Geology). Continuous predictor variables with positive and negative coefficients have, respectively, independent positive and negative correlations with outburst probability (Table 4). All predictor variables are statistically significant at the 0.05 level, but M_hw is highly significant ($p<0.0001$) (Table 3).

The formula for estimating outburst probability can be expressed, using Eq. (4), as:

$$P(Y=1)=\{1+\exp-[\alpha+\beta_1(\mathrm{M\_hw}) + \Sigma\beta_{\mathrm{j}}(\mathrm{Ice\_core_j})+B_2(\mathrm{Lk\_area}) + \Sigma\beta_k(\mathrm{Geology}_k)]\}^{-1}, \quad (5)$$

where $\alpha$ is the intercept, and $\beta_1$, $\beta_2$, $\beta_{\mathrm{j}}$, and $\beta_{\mathrm{k}}$ are regression coefficients for M_hw, Lk_area, Ice_core, and Geology, respectively (Table 4). The measured values of continuous variables M_hw and Lk_area can be entered directly into the equation. In contrast, indicator variables must be used for the nominal variables Ice_core and Geology. $\mathrm{Ice\_core_j}$ equals 1 if the moraine dam is ice-cored and 0 if the moraine dam is ice-free, and $\mathrm{Geology}_k$ equals 1 if the main rock type forming the moraine dam is $k$ and 0 otherwise (Table 4). The significance of the fitted logistic regression model was tested by comparing the negative log-likelihood of the full model to that of the reduced (intercept-only) model. The result is highly significant ($p<0.0001$, Table 5). Application of the formula to all lakes in the study area generated a distribution of probability estimates ranging from $6.1\times10^{-6}$ to 77% (Fig. 4). Only lakes with moraine dams composed of metamorphic rock material, however, have outburst probability estimates less than 0.2%.

## 8. Predictive capability of the model

A statistical model's predictive capability must be evaluated before it can be used in hazard assessments. Ideally, predictive success is assessed by applying the model to an independent data set in the study area from which the training sample was taken. Unfortunately, too few drained lakes exist in the study area to set aside a portion for subsequent model validation. If data are limited, it is preferable to base a statistical model on all the data than to generate a model from a portion of the available data and set aside the remainder for validation (I. Bercovitz, personal communication, 2005). Our model's predictions were therefore cross-validated with the observations on which the model was based.

In order to determine the proportion of successful predictions, I initially used an outburst probability cutoff value of 50%, above which lakes are classified as drained and below which lakes are classified as undrained. A 50% cutoff value is the default in most statistical programs (e.g., JMP, SAS Institute Inc., 2003) and commonly used in the literature (e.g., Dai and Lee, 2003). Based on this cutoff, the logistic regression model

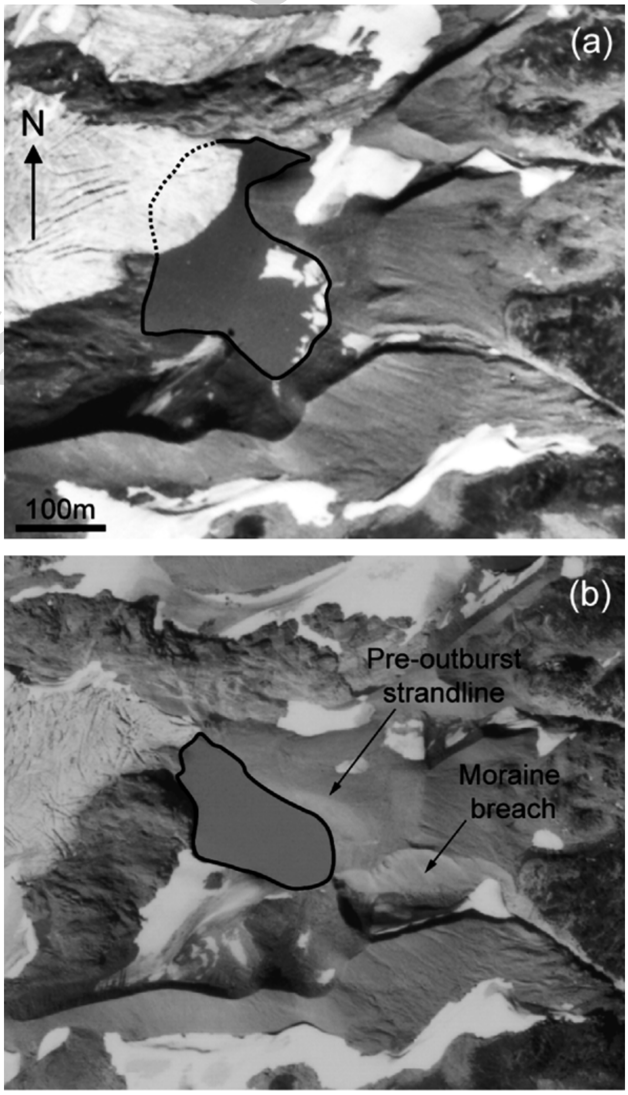


Fig. 8. Unnamed moraine-dammed lake above the Gilbert Glacier in the southern Coast Mountains (black star in Fig. 1) (a) before and (b) after a partial outburst. Aerial photographs (a— BC1218-22; July 17, 1950; b— 30BCC03025-54; September 3, 2003) reproduced with permission of the Province of British Columbia. Other aerial photographs constrain the date of the outburst to between July 1965 and September 1977.

correctly predicts 99% of the undrained lakes, but only 40% of the drained lakes; the overall predictive accuracy is 92% (Table 6). Begueria and Lorente (2002) state that an overall accuracy greater than 70% is good in most classification applications.

The proportion of true positives (40%) is referred to as the model's sensitivity; the proportion of true negatives (99%) is the model's specificity. The trade-off between a model's sensitivity and specificity is illustrated in the receiver operating characteristic (ROC) curve (Fig. 5). A ROC curve is a plot of a predictive model's sensitivity versus its false positive (i.e. 1— specificity) rate, according to all possible classification cutoff values (Austin and Tu, 2004). The area under the ROC curve provides a measure of the model's diagnostic ability (Hanley and McNeil, 1982). A straight line with a 45° slope represents a model with no predictive capability (area under the curve is 0.5). In contrast, a vertical line coincident with the sensitivity axis represents a model that correctly predicts all cases (area under the curve is 1.0). The area under our model's ROC curve is 0.869, which is comparable to values reported for successful predictive models in other disciplines (Austin and Tu, 2004).

The arbitrary probability cutoff threshold must be decreased to increase the sensitivity, or conservativeness, of a model for use in hazard assessments. A more sensitive model, however, will generate more false positives. Pagano and Gauvreau (2000) recommend decreasing the threshold to the point on the ROC curve closest to the upper-left corner, which corresponds to the probability threshold that simultaneously maximizes sensitivity and specificity, 19% in this study.

Both the specificity and sensitivity of the model change if we use a probability threshold of 19% instead of the default 50% to evaluate the model's predictive success. The specificity decreases slightly to 90%, which corresponds to an increase in the number of false positives, but the sensitivity improves substantially to 70% (Table 6). With a 19% cutoff, the logistic regression model now correctly classifies 14 of the 20 drained moraine-dammed lakes in the study area (Fig. 6).

Given the number of possible trigger mechanisms for moraine dam failures and the relatively small sample size on which the predictive model is based, we recommend categorizing probability estimates. Using probability ranges or intervals instead of discrete values ensures that estimates do not convey more precision than is warranted. Numerous researchers arbitrarily categorize probabilities, particularly for display purposes (e.g. Dai and Lee, 2003), but a curve showing the cumulative percentage of drained

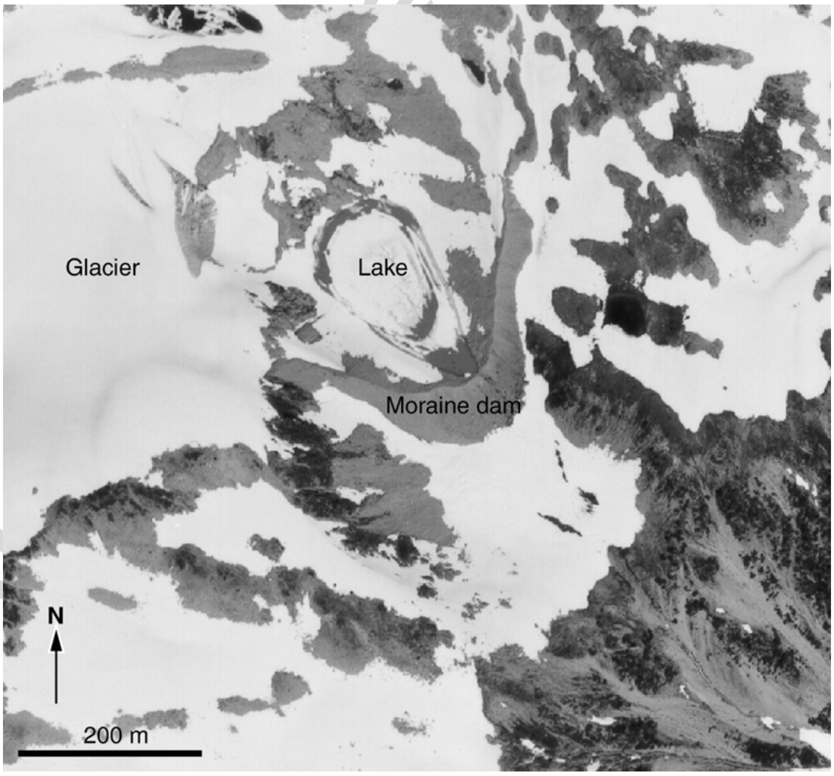


Fig. 9. Undrained moraine-dammed lake west of Scherle Peak (black triangle in Fig. 1), which, according to Eq. (5), has a "very high" outburst probability of 61%. Note the narrow footprint and steep distal flank of the moraine dam. Aerial photograph 30BCC97087-036 (July 20, 1997) reproduced with permission of the Province of British Columbia. Field investigations during July 2005 confirm that the lake still exists.

lakes versus probability provides a more objective basis for defining probability thresholds. We classify outburst probabilities as very low (<6%), low (6–12%), medium (12–18%), high (18–24%), and very high (>24%), based on the probabilities of the breaks in slope in Fig. 7.

We demonstrate the application of the model retrospectively by presenting the four relevant measurements and resulting probability equation for an unnamed lake within our study area that partially breached its moraine dam sometime between July 29, 1965 and September 11, 1977 (Fig. 8; see Fig. 1 for location). Prior to the outburst, the lake had an *area* of 4.0 ha. Its *ice-free* moraine dam is composed of *volcanic* rock and has a *height-to-width ratio* of about 0.3. Substituting the continuous variable values and appropriate nominal variable indicator values into Eq. (5), $P(\text{outburst}) = \{1+\exp-[-7.1074+(9.4581)*(0.3)+(1.2321)*(1)+(0.0159)*(4.0)+(3.1461)*(1)]\}^{-1}$, yields a “very high” outburst probability of 52%.

The main purpose of the model, of course, is to help identify undrained moraine-dammed lakes with high outburst probabilities. One such lake exists at an elevation of 2180 m in the Dickson Range, 2.5 km west of Scherle Peak (Fig. 1). The unnamed lake is impounded behind a lobate moraine dam with a steep distal flank, and the snout of a small, retreating glacier is currently a few hundred metres from the proximal lakeshore (Fig. 9). The lake has an *area* of 2.0 ha, and its *ice-free* moraine dam, composed predominantly of *granitic* rock, has a *height-to-width ratio* of 0.5. The appropriate substitution of predictor variable values into Eq. (5), $P(\text{outburst}) = \{1+\exp-[-7.1074+(9.4581)*(0.5)+(1.2321)*(1)+(0.0159)*(2.0)+(3.1461)*(1)]\}^{-1}$, yields a “very high” outburst probability of 61%. This example demonstrates how the model can be used to help remotely identify potentially hazardous lakes for more detailed field investigations.

## 9. Discussion

### 9.1. Implications of the four predictor variable logistic regression model

The entry of only four predictor variables into the logistic regression model has important implications. According to the model, the outburst probability of a given lake in our study area depends most on M_hw (Table 3). The implication of the positive regression coefficient, that outburst probability increases as moraine dams become higher and narrower, supports qualitative assessments of conditions that predispose a moraine dam to fail (Chen et al., 1999; Clague and Evans, 2000; Richardson and Reynolds, 2000; Huggel et al., 2004). Water flowing over a narrow moraine dam need erode only a small volume of sediment from the distal flank and crest before incision reaches the lakeshore and catastrophic failure begins.

Lk_area, another variable in the logistic regression model, also has a positive regression coefficient. Thus, all other things being equal, outburst probability in the study area increases with increasing Lk_area. Although the surface area of a lake, in itself, does not affect outburst probability, we included Lk_area because it is proportional to lake volume (O'Connor et al., 2001; Huggel et al., 2002) and, probably, lake depth at the moraine dam. We interpret the significance of Lk_area in the model as an indication that a lake with a relatively large surface area and, therefore, greater depth and volume is more susceptible to catastrophic drainage due to high hydrostatic pressure on the moraine dam.

The entry of Geology into the final model implies the sedimentology of the moraine dam may influence outburst probability. Clague and Evans (2000) imply that moraine dams with a large proportion of boulders will better resist catastrophic incision of their outlet channels than dams composed mainly of sand and gravel. Therefore, bedrock that is prone to intense glacial comminution may form especially erodible moraine dams. In our study area, moraine dams composed dominantly of sedimentary rock debris have a higher likelihood of failure than dams composed of more competent or resistant rock debris. The dependence of the outburst probability model on Geology highlights the need for field investigations in addition to remote hazard assessments.

Three implications of the four predictor variable model described above seem counterintuitive. First, the model suggests, all other things being equal, that ice-cored moraine dams are less likely to fail than ice-free moraine dams (Table 4). This result suggests the model does not capture the temporally-related enhancement of moraine dam failure potential while a moraine is downwasting due to ice-core melting (Richardson and Reynolds, 2000). Reynolds et al. (1998), Richardson and Reynolds (2000), and Yesenov and Degovets (1979) have shown, however, that subsidence of ice-cored moraine dams due to melting can increase a dam's susceptibility to catastrophic failure. We suggest three possible explanations for our model's contradictory implication. First, ice-cored moraine dams in our study area are smaller than those that have failed in the Himalayas (Watanabe et al., 1994) and, therefore, undergo only minor subsidence through melting. Second, most ice-cored moraine dams are broader and more rounded than ice-free dams (Ostrem and Arnold, 1970) and thus are more slowly eroded by overflowing water. Third, a moraine dam containing an ice-core may better resist incision during anomalous overflow events than a moraine dam comprising only unconsolidated sediment.

The absence in the model of all six candidate predictor variables associated with glaciers (Tables 1 and 3) implies that a lake's susceptibility to ice avalanches is, in itself, not a good indicator of its outburst probability. Exclusion of all glacier-related predictor variables was unexpected, given that most known moraine dam failures were caused by overtopping waves triggered by ice avalanches (Ding and Liu, 1992; Richardson and Reynolds, 2000). One possible explanation is that the proportion of drained moraine-dammed lakes situated beneath glaciers is not significantly different from the proportion of undrained lakes situated beneath glaciers.

Many authors have emphasized the contribution of topographic setting to a moraine-dammed lake's likelihood of draining catastrophically (Lu et al., 1987; Richardson and Reynolds, 2000; O'Connor et al., 2001). O'Connor et al. (2001) schematically illustrate three different "topographic setting criteria" for evaluating the potential for a moraine dam to fail. Our model suggests, however, that the moraine dam itself may contribute most to outburst probability. Not only is M_hw entered first in the stepwise procedure (Table 3), but the three other predictor variables in the final logistic regression model relate to the moraine dam. M_hw, Ice_core, and Geology are descriptive characteristics of the moraine, established during its deposition. Lk_area is also determined during moraine formation because it is a function of moraine height (O'Connor et al., 2001). The significance of this finding is that on-site hazard assessments of moraine-dammed lakes may overemphasize the importance of the topographic setting and underemphasize the importance of the moraine dam itself.

The four predictor variables that were entered into the final logistic regression model best classify the lakes in our study area as undrained or drained according to their observed status. We are reluctant to say with certainty, however, that these variables are, in fact, true independent predictors of outburst probability in our study area without first performing bootstrap resampling (Austin and Tu, 2004). The premise of bootstrap resampling, in this application, is that only those predictor variables that are consistently entered into models generated from hundreds to thousands of randomly selected subsamples of the original data set are true independent predictors of outburst probability.

### 9.2. Implications of a drained lake classification

The main goal of this research was to identify moraine-dammed lakes in southwestern British Columbia that have a high probability of catastrophic drainage. Therefore, the classification of an undrained lake as drained does not represent a flaw in the predictive model. According to Begueria and Lorente (2002), false positives can be considered cases where a high probability of outburst exists, "but no events have been observed within the sample period, due to the rarity of the process" (p. 19). If a lake's outburst probability estimate is high or very high ($>18\%$), the lake is simply more similar to the drained lakes than to the undrained lakes on which the statistical model was based. In other words, the lake's moraine dam is more likely to fail catastrophically than it is to erode gradually over time.

Land-use planners, of course, require an estimate of the period within which a moraine dam is likely or unlikely to fail. A common approach for estimating the probability of occurrence $P$ of a debris flow in a particular channel or region, during a period of $n$ years, uses the binomial formula (e.g., Jakob, 2005), $P(\text{debris flow}) = 1-(1-1/T)^n$, where $T$ is the return period of debris flows. This approach cannot be used to estimate the timing of a lake outburst, however, because moraine dam failures are generally non-recurrent. An alternative method that is appropriate for isolated events is needed.

Initially, we may hypothesize that lakes with relatively high outburst probabilities will drain sooner than lakes with relatively low outburst probabilities. For instance, a lake with a probability estimate of 40% will, on average, breach its moraine dam before a lake with an estimate of 20%. If we could establish a correlation between outburst probability estimates and the time since lake formation for lakes to drain catastrophically, we could specify periods within which moraine dam failure is or is not likely. We plotted our probability estimates for drained lakes against their approximate longevities to determine whether a relation exists between our outburst probability estimates and the time to failure. We assumed that the lakes begin to form with the abandonment of Little Ice Age terminal moraines (~1900 A.D. in the study area; Ryder and Thomson, 1986). Unfortunately, the data revealed no statistically significant trend. We, therefore, conclude that our approach generates estimates of outburst probability, based on certain moraine dam characteristics, without implying a period within which moraine dam failure is or is not likely to happen.

Although we cannot specify the period to which our probability estimates apply, we can provide land-use planners and decision makers with the probability that a moraine-dammed lake will actually drain catastrophically, given that our model predicts it will drain catastrophically (positive test). According to Bayes' theorem, this conditional probability can be expressed as:

$$`\mathrm{P}(D|T^{+}) = [P(D)*P(T^{+}|D)] \;/\; \{[P(D)*P(T^{+}|D)] + [P(U)*P(T^{+}|U)]\}, \quad (6)$$

where $P(D)$ is the prior probability that a moraine-dammed lake will drain catastrophically, $P(U)$ is the prior probability that a moraine dam will not drain catastrophically, $P(T^{+}|\, D)$ is the sensitivity, and $P(T^{+}|\, U)$ is 1 minus the specificity (Pagano and Gauvreau, 2000). After substituting the appropriate values (Fig. 6) into Eq. (6), we determine $P(D|T^{+})$ is about 0.44. The probability that an existing lake classified as drained will actually drain catastrophically is thus 44%.

### 9.3. Potential sources of error

The reliability and robustness of a statistical model depend, in part, on the quality of the data on which it is based. Erroneous predictions can arise from several possible aerial photograph interpretation errors. First, the type of dam impounding a lake may be misinterpreted due to snow cover, cloud cover, shadows, distortion due to high relief terrain, or the presence of a morainal veneer over bedrock. Second, photogrammetric measurements may be inaccurate due to limitations imposed by aerial photograph scale, object clarity, object size, and the skill of the interpreter (Avery and Berlin, 1985). In this study, percentage errors for vertical and horizontal distance measurements were evaluated by comparing aerial photograph and ground measurements. Vertical measurement error was particularly sensitive to object height. Percentage errors for objects more than 50 m high were consistently less than 10%, whereas errors for objects less than 10 m high reached 60% (Table 2). We were able to plot features in their correct planimetric positions using Lillesand and Kiefer's (2000) approach for correcting for relief displacement on a point-by-point basis. Thus, percentage errors for horizontal distance measurements were generally less than 5% and never exceeded 10% (Table 2). Third, measurements of moraine width and, therefore, height-to-width ratio can be imprecise. Because the toe of the proximal flank of the moraine dam is commonly below the lake surface, moraine width was measured from the lakeshore to the toe of the distal flank of the moraine (Fig. 3). As a result, height-to-width ratios of moraine dams with gentle proximal flanks, in particular, may be too large. Fourth, and perhaps most important, lake status can be equivocal. The criteria for classifying a lake as drained include a distinct V-notch in the moraine dam, a coherent, disproportionately large debris fan directly below the dam, and evidence of catastrophic flooding in the valley below. In a few cases, normal erosional and depositional processes and vegetative establishment make lake classification difficult. Lake misclassification may have a significant impact on the predictive model.

Sample size, in a strict sense, is not a source of error, but it has an effect on model reliability. It is not unreasonable to base a statistical model on a data set of 186 lakes, but the results are more reliable where the proportion of 1 s (events) is similar to the proportion of 0 s (non-events) (King and Zeng, 2001; Dai and Lee, 2003). In our study, only 20 out of 186 lakes produced outburst floods. Because statistical models such as logistic regression tend to underpredict the probability of rare events (King and Zeng, 2001), it is not surprising that three-quarters of our outburst probability estimates are less than about 13% (Fig. 4).

The distribution of observed values of a particular categorical predictor variable also can have a substantial effect on probability estimates. In our study, for example, none of the 11 lakes impounded by dams derived from metamorphic rocks has produced an outburst flood. As a result, the coefficient associated with metamorphic moraine dams is negative and, compared to the coefficients associated with other moraine dams, is large (Table 4). Outburst probability estimates for granitic, volcanic, or sedimentary moraine dams range from 0.2 to 77%, whereas estimates for metamorphic moraine dams range from $6.1\times10^{-6}$ to only 1.5%. Thus, our model yields low estimates of outburst probability for metamorphic moraine dams, regardless of the values of other predictor variables. A future expansion of our study area and database would facilitate development of an outburst probability model that is less biased by small sample size.

### 9.4. Applicability of results

In spite of the possible errors, our statistical model provides a first step toward objectively and quantitatively estimating outburst probability. The predictive model should not be incorporated into hazard assessments, however, without first acknowledging the issues that may limit its applicability. For example, incorporating drained lakes from outside the study area to increase the number of 1 s violates the otherwise random, or in this case complete, sampling scheme. The effect on the predictive model of supplementing the sample of drained lakes with foreign, although morphologically similar, drained lakes is uncertain.

An approach based on remote sensing limits the use of our methodology to regions with similar data sources. We used large-scale aerial photograph stereopairs, but overlapping, high resolution satellite images such as those taken by the IKONOS (1 m resolution in panchromatic band) and QuickBird (0.6 m resolution in panchromatic band) satellites may also be used for the measurement of the four predictor variables. Advantages of satellite imagery include the opportunity to use multispectral imagery to rapidly detect glacial lakes (Huggel et al., 2002), the currency and uniform regional coverage of images, and the relatively easy visualization, manipulation, and analysis of images in a geographic information system. In regions such as the Alps, where access to moraine-dammed lakes is not difficult, field measurements can provide an alternative basis for statistical analysis.

Our model for estimating outburst probability is only applicable to the population from which the statistical sample was taken, that is lakes between Fraser and Klinaklini rivers in the southern Coast Mountains. We, therefore, recommend using the model only as a general guide in neighbouring watersheds or in regions with similar physiography and moraine dam morphologies. The applicability of our results to other mountain ranges, such as the Andes or Himalayas, is uncertain. Andean and Himalayan moraine-dammed lakes differ from those in our study area. They are commonly shadowed by steep slopes with local relief of thousands of metres, which influences the rate and magnitude of rockfalls and ice avalanches into the lakes. Second, Andean and Himalayan moraine dams are generally larger and more bulky than moraine dams in southern British Columbia (Richardson and Reynolds, 2000). Third, Andean and Himalayan lakes commonly form through coalescence of supraglacial ponds on stagnant, downwasting debris-covered glaciers (Watanabe et al., 1994; Richardson and Reynolds, 2000). Different mechanisms may control the catastrophic drainage of these ice-contact moraine-dammed lakes. In general, we expect the reliability of our model to decrease with increasing distance from our study area and with increasing disparity in moraine-dammed lake characteristics. It is more appropriate to use our methodology, than the results of our study, to develop a region-specific model for estimating outburst probability.

Even within our study area, the model should only be used for preliminary assessments of outburst probability. The model has not been independently validated due to the rarity of outburst floods in the study area. Furthermore, follow-up field investigations may be necessary to identify unique, potentially hazardous conditions that cannot be documented through aerial photograph interpretation alone. The model does not eliminate the need for on-site measurements. Rather, it is designed to provide professionals with a tool for objectively prioritizing the order in which detailed field investigations of potentially hazardous moraine-dammed lakes are carried out.

## 10. Conclusion

Most outburst floods from moraine-dammed lakes in British Columbia have caused little damage. However, as development pushes farther into formerly remote mountain valleys, the likelihood of damage and injury from such floods will increase. Accordingly, professional engineers and geoscientists will be required to complete assessments of hazards posed by moraine-dammed lakes. We propose an objective method, based on measurements derived from aerial photographs and maps and logistical regression analysis, for making preliminary assessments of the probability of catastrophic draining of moraine-dammed lakes. The method is quick, inexpensive, and yields reproducible results. The model selects variables that discriminate best between drained and undrained lakes and highlights the need to further study the contribution of the moraine dam itself to outburst probability. Logistic regression allows the conservativeness of predictions to be adjusted to suit different applications. Engineers and geoscientists, however, should use our method only as a tool for making preliminary assessments of outburst probability, to be followed by detailed field investigations.

## Acknowledgements

The research was supported by an NSERC Postgraduate Fellowship to Robin J. McKillop and an NSERC Discovery Grant to John J. Clague. Tracy Brennand provided direction during the early stages of the research, and Matthias Jakob made valuable suggestions on data analysis techniques. We thank Michelle Hanson, Jeff Moore, Fred Touche, Dave Campbell, Tim Blair, Michael Morris, Don Funk, and Steve Yan-Klassen for their assistance in the field. Jim O'Connor kindly provided aerial photographs and maps of breached moraine dams in Washington and Oregon, Ian Bercovitz provided statistical advice, and Jennifer Butler provided assistance in the B.C. Aerial Photograph Warehouse. We appreciate helicopter support provided by John Goats (Pemberton Helicopters) and Mike King (White Saddle Air Services). Reviews by Christian Huggel and Jeffrey Coe helped improve the quality of this paper.

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