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Landslide inventory in a rugged forested watershed: a comparison between air-photo and field survey data

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Abstract

Landslide inventories are routinely compiled by means of aerial photo interpretation (API). When examining photo pairs, the forest canopy (notably in old-growth forest) hides a population of "not visible" landslides. In the present study, we attempt to estimate how important is the contribution of landslides not detectable from aerial photographs to the global mass of sediment production from mass failures on forested terrain of the Capilano basin, coastal British Columbia. API was coupled with intensive fieldwork for identification and measurement of all landslides. A 30-year framework was adopted. We show that "not visible" landslides can represent up to 85% of the total number of failures and account for 30% of the volume of debris mobilised. Such percentages display high sub-basin variability with rates of sediment production varying by one order of magnitude between two sub-basins of the study area. This is explained qualitatively by GIS-based analysis of slope frequency distributions, drainage density, and spatial distribution of surficial materials. Such observations find further support in the definitions of transport-limited and supply-limited basins. As a practical consideration to land managers, we envisage that supplementary fieldwork for landslide identification is mandatory in transport-limited systems only. Fieldwork has demonstrated that gully-related failures have a greater importance than one could expect from API.

Keywords: Landslide identification; Air-photo interpretation; Interbasin variability; Forested terrain; Coastal British Columbia

1. Introduction

Despite of the great advances in remote sensing technology, compilation of landslide inventories in rugged forested terrain, the first fundamental phase to evaluating landslide hazard for land use planning and development (Wieczorek, 1984), is routinely performed by means of aerial photo interpretation (API) and limited fieldwork. When examining photo pairs, the forest canopy (notably in old-growth forest) hides a population of "not visible" landslides (Fig. 1). Reid and Dunne (1996) assert that most landslides are readily identified on aerial photographs. They acknowledge the existence of a minimum landslide size visible on photographs that must be determined with the aid of field measurements. The advice given is that the frequency of occurrence of smaller and "not visible" landslides must be estimated. The problem

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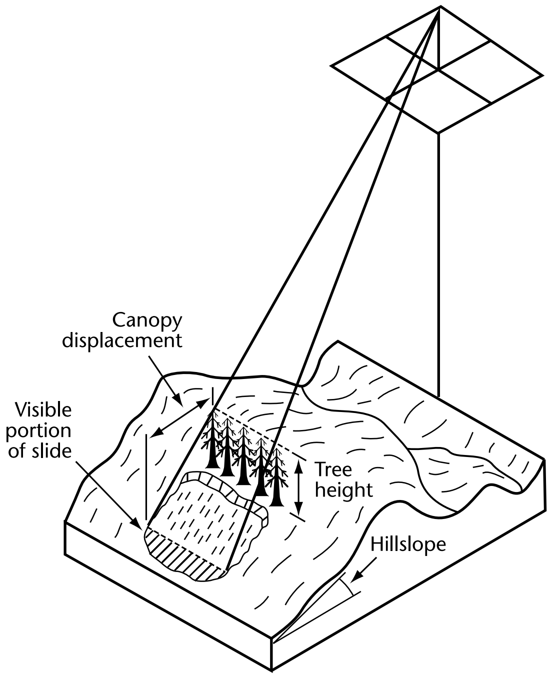

Fig. 1. Sketch diagram showing canopy displacement and visible portion of a landslide as seen from an aerial photograph (modified after Pyles and Froehlich, 1987).

discussed here is that there are no clear guidelines for the estimation procedure required.

Most of the published literature addresses the question of landslide identification in empirical ways (e.g., O'Loughlin, 1972; Rood, 1984; Schwab, 1988; Rollerson et al., 2001). In fact, under the assumption that the incidence of 'not visible' landslides is negligible to the whole picture of the inventory, such studies exclude events below a certain size (threshold) that is considered still to be assuredly photo-detectable in recent harvested cut-blocks and in primary forest. Interestingly enough, in British Columbia, this threshold appears to have increased over time. O'Loughlin (1972) considered debris slides and avalanches larger than 93 m^2; Rood (1984), events larger than 200 m^2; Schwab (1988), larger than 400 m^2 and, Rollerson et al. (2001), larger than 500 m^2.

The importance of the question of "not visible" landslides became apparent after the 1996 floods in Oregon. Some environmental groups did a flyover inspection and reported high slide frequency in cut and roaded areas, while others were concerned that many slides were missed in the forested areas. A good reference datum against which to evaluate management impact was simply not available (F.J. Swanson, United States Department of Agriculture, Pacific Northwest Research Station, Oregon, personal communication, 2001). As a consequence, the Oregon Department of Forestry initiated a large project (Robison et al., 1999, to date the only study) to systematically compare ground-based landslide inventories with air-photo-based inventories. About half of the landslides in recent plantations were visible in photos at the 1:6000 scale. In mature and old-growth forest, the air photos revealed 5% (at most) of the ground-surveyed slides. Such percentages should not surprise the reader, as landslide size in the Oregon Coast Range is typically smaller than any of the air-photo thresholds reported in the literature (e.g., O'Loughlin, 1972; Rood, 1984; Schwab, 1988; Rollerson et al., 2001). However, there are two limitations to Robison et al. (1999) study: (i) they counted and measured only those failures that impacted stream channels; and (ii) the study focused on areas considered to have experienced the most severe impacts from the 1996 storms.

The main purpose of this study is to critically evaluate the use of air photographs in the study of landslide incidence in both clearcut and forested terrain. Our goal is to determine how large a proportion of failures is missed, both in terms of number of events and volume of mobilised debris, at a given air-photo scale. Specifically, we aim to see whether the proportion of "missed" events is constant throughout a single physiographic region (the Pacific Ranges of the Coast Mountains) so that our findings can be generalised to the regional scale. Lastly, we will test whether identification of "not visible" events can affect (i) estimated rates of sediment delivery to streams; and (ii) conclusions about the impact of logging on slope stability.

2. Study area

The study was conducted in the Capilano River basin, a 198-km^2 watershed located in West Vancouver, British Columbia. The site was selected for the following reasons: (i) forest harvesting has been performed with well-defined and documented techniques over the last 50 years; (ii) it is a water supply area for Greater Vancouver, hence a wide range of thematic maps and detailed air-photo coverage are available; (iii) geology is relatively homogeneous; and (iv) it is the most easily accessible forested watershed that meets our experimental requirements.

The watershed (Fig. 2) lies within the Pacific Ranges of the Coast Mountains (Holland, 1976). The most striking feature of the Capilano valley is rugged topography, with slopes typically steeper than 35° and steepness generally increasing with elevation. The rugged landscape is the result of the combined effects of tectonic uplift, rock strength, and glacial erosion. Bedrock consists primarily of intrusive igneous rocks—granodiorite, quartz diorite, diorite, and lesser amounts of gabbro and migmatite. Limited metamorphic-dominated formations are present in places (i.e., Gambier Group and Twin Islands Group; Roddick, 1965). Gentle and moderate slopes, especially at mid to low elevations, are mantled by glacial till, which is the most extensive surficial material and constitutes the primary source of fine sediments. Surficial materials deposited on hillslopes in post-glacial time consist primarily of colluvium.

The climate in the Pacific Ranges of the Coast Mountains consists of two main seasons. A wetter one, from October through May, is characterised by an almost uninterrupted series of large-scale oceanic storms that encroach upon the coast. A much drier regime characterises June through September, when only intense small-scale oceanic storms disrupt the persistent high-pressure domain. Accordingly, in the Capilano watershed (at the reservoir outlet), about 80% of the annual precipitation falls during the wet season. Minimum monthly totals occur in July and August, accounting for about 4% of the normal annual precipitation.

Convergence in valleys and topographic uplift tend to increase precipitation abruptly north of the Lower Mainland, where fronts encounter the Pacific Ranges. Annual precipitation ranges from 2000 mm at Cleveland Dam to 5000 mm at Mt. Hollyburn (1325 m) and Mt. Strachan (1454 m; Fig. 2). Elevation also affects the snowfall proportion of total precipitation. Measurements from snow courses show that at elevations of around 1000 m the normal maximum water equivalent in the snow pack is at least 1600 mm (Greater Vancouver Regional District, 1999).

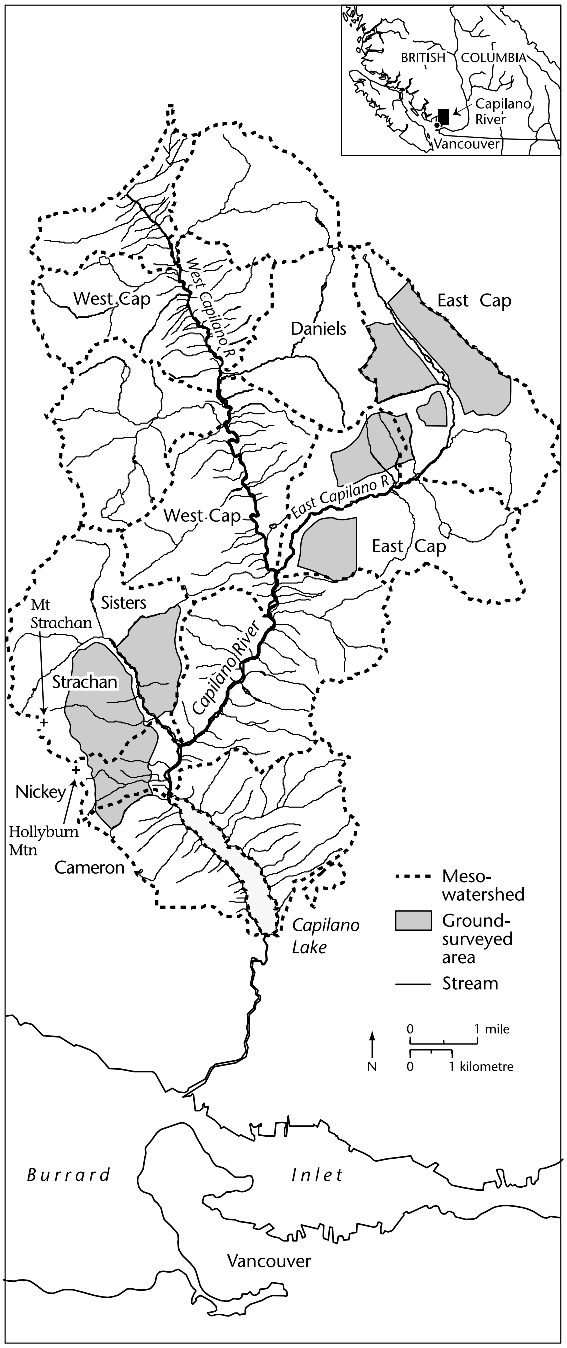

Fig. 2. Map of the Capilano watershed indicating the location of the ground-surveyed areas.

3. Methods

3.1. Field and air-photo surveys

The study entailed the compilation of a landslide inventory through API. The scale of aerial photography available ranges from 1:12,000 to 1:15,000. Photo sets date from 1968, 1976, 1984, 1992, and 1996 (plus helicopter flyovers in July 2000). Within the watershed, intensive ground checking was conducted successively on Sisters and East Cap Creeks (Fig. 2). The two subwatersheds were selected for their topographic, land use, and logistic attributes: Sisters Creek is the closest location presenting areas of old extensive logging (Fig. 3A) on steep terrain (class IV and V polygons; cf. Table 1), while East Cap Creek is the most easily accessible site with recent cut-blocks (Fig. 3B) on similarly steep slopes. These basins present the opportunity to conduct meaningful comparisons among undisturbed forest, recent "careful" clearcut, and old extensive logging. Land use covers in the surveyed areas of the two creeks are reported in Table 2.

Detailed fieldwork was conducted with the purpose of identifying and measuring every distinguishable slope failure within each traversed terrain polygon. Following British Columbia Terrain Stability Classification guidelines of the British Columbia Forest Practices Code (British Columbia Ministry of Forests, 1995, cf. Table 1), J.M. Ryder and Associates compiled the terrain stability and surficial material mapping of the watershed. The classification was conducted mainly by API, with only 25% of terrain polygons ground-checked at the time of map compilation. In every study polygon, we walked along the entire gully network and covered the whole area of the polygon. We can assert with confidence that we detected all existing landslides within each polygon.

The inventories were carried out with the following operational specifications: (i) by examining ground classified in British Columbia stability classes III, IV, and V (Table 1), terrain polygons were selected in such a way that every slope aspect was proportionally represented in each sub-basin; (ii) all traversed, "not visible" events were systematically measured; (iii) road-related landslides were not included because there has been continuous road maintenance in the watershed, and an indefinite number of landslide scars have been rehabilitated; and (iv) only those mass wasting events that occurred during the last 30 years were considered (Fig. 4). The temporal framework was determined on the basis of earlier studies (Smith et al., 1983, 1986; Rood, 1984; Reid and Dunne, 1996) and of the uncertainty involved in the identification of old, small, slope failures (e.g., Wieczorek, 1984).

Minimum ages of landslides were estimated in the field by means of dendro-chronology, branch level counts on saplings, and presence of 1- to 2-year litterfall on the scar; and on aerial photos through stereoscopic inspection of sequential photo sets. Photo interpretation was conducted with a SOKKIA MS27 stereoscope (3 × and 8 × magnification) and was supervised by J.M. Ryder and Associates. Each mass movement event, when possible, was partitioned into initiation, transportation, and deposition zone. The technique adopted to evaluate the mobilised volume associated with each failure was that described by Rood (1984).

Episodic and recurrent mass failures were differentiated and then classified according to whether they were active or dormant (Zaruba and Mencl, 1969; Erskine, 1973; Wieczorek, 1984; Yanai and Usui, 1987). This distinction is relative to a specific time frame (cf. Flageollet, 1996, for an extended discussion on the time dimension in the study of landslides). In our case, dormant (inactive or fossil) mass movements were taken as those that, although still visible on air photos, had occurred more than 30 years ago. These last were not taken into consideration. Especially at places of recurring landslide occurrence (i.e., gully-channels and -sidewall), scars were not always the result of a one-off event, indeed sometimes they resulted from the occurrence of overlapping, repeated events, or from remobilisation of antecedent failure deposits. In the former case, when recognisable, only the scar of the most recent event was measured, and events associated to debris remobilisation were not considered. Following these criteria, a quantitative database was obtained from the integration of fieldwork and API (Fig. 4).

3.2. Statistical analysis

The land base was subdivided into polygons according to British Columbia terrain classification

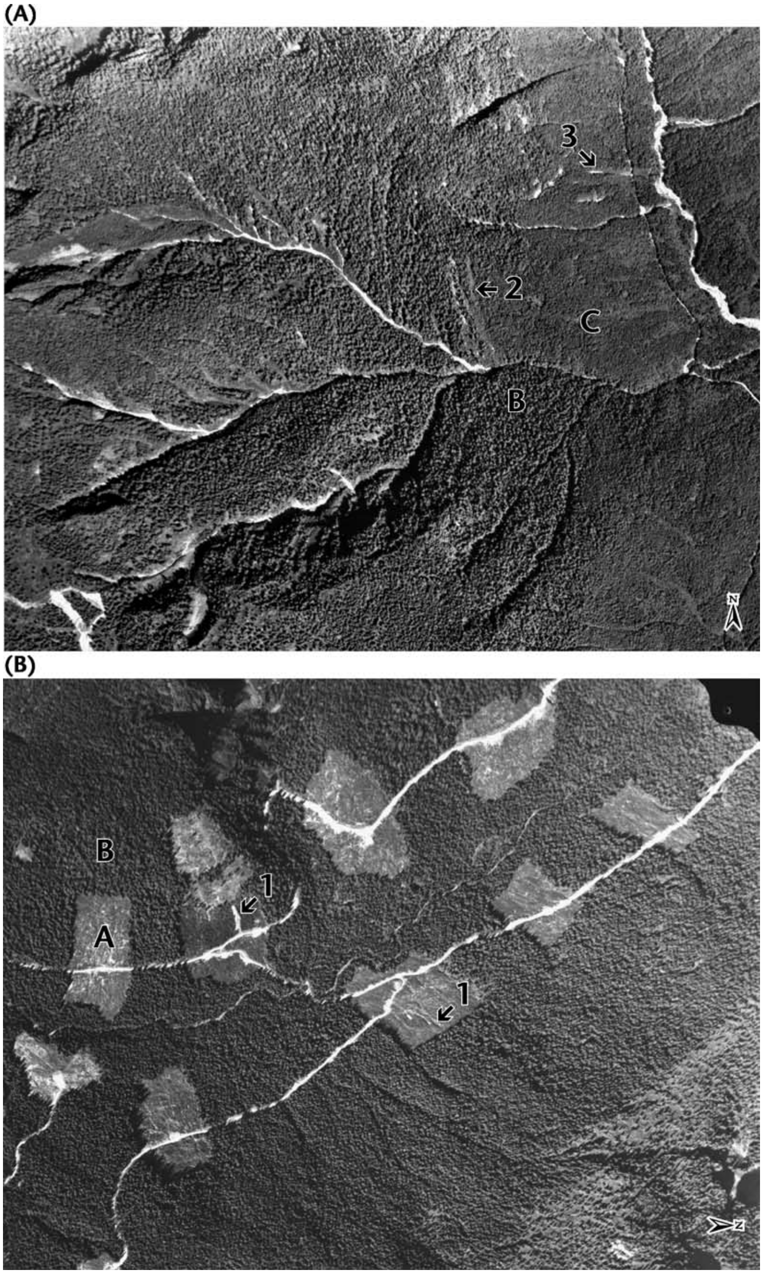

Fig. 3. Aerial photographs taken in 1996 showing part of (A) Sisters Creek and (B) East Cap Creek basins. Note the higher degree of landscape dissection in Sisters Creek when compared to East Cap Creek. Examples of types of forest cover are marked with capital letters: A = recent cut-blocks, B = old-growth forest, C = old extensive clearcut. Examples of visible mass movement scars are marked with numbers: 1 = debris slides in recent cut-blocks, 2 = debris flows in old-growth forest reaching Strachan Creek, 3 = debris slide on old clearcut crossing a logging road and reaching Sisters Creek.

Table 1
British Columbia Terrain Stability Classification[a]

Terrain stability class	Subjective rating system	Interpretation
I	Flood plains and level to undulating coastal plain areas Most terrain with slopes < 20%	No significant stability problems exist
II	Most gently sloping (20–40%), poorly to well drained, lower slope landforms Moderately sloping (40–60%), well to rapidly drained surficial deposits	Very low likelihood of slides following logging or road construction Minor slumping is expected along road cuts, especially for 1 or 2 years following construction
III	Moderately sloping (40–60%), imperfectly to poorly drained surficial deposits that are not marine or lacustrine Level to gently sloping (0–40%), imperfectly to poorly drained, deep marine clays and lacustrine deposits Moderately sloping, deeply gullied surficial deposits that are not of lacustrine or marine origin	Minor stability problems can develop Timber harvesting should not significantly reduce terrain stability; there is a low likelihood of landslide initiation following logging Minor slumping is expected along road cuts Low likelihood of landslide initiation following road building
IV	Steeply sloping (>60%), well drained, deeply gullied surficial deposits Steeply sloping, poorly drained surficial deposits Moderately sloping, deeply gullied, or imperfectly to poorly drained lacustrine or marine deposits	Expected to contain areas with a moderate likelihood of slide initiation following logging or road construction
V	Any areas where natural landslide scars are visible on air photographs or in the field Very steeply sloping (>70%), imperfectly to poorly drained, deeply gullied surficial deposits	Expected to contain areas with high likelihood of slide initiation following logging or road construction

[a] Modified from British Columbia Ministry of Forests, 1995.

guidelines (Table 1). A polygon was considered as an experimental unit, and each polygon that received the same classification ("treatment," i.e., survey type, land use, stability class) was regarded as a replication. Two different types of survey to calculate landslide density and the associated amount of mobilised volume of debris were conducted: (i) exclusively by API; and (ii) by API coupled with intensive field survey. Control on experimental error was achieved by selecting study sites with homogeneous climate, geological setting, and vegetation cover. Confounding factors were minimised by comparing polygons of equal land use and stability (according to the British Columbia Terrain Stability Classification).

A two-step statistical analysis was performed. First, one-way ANOVA-like tests were conducted to evaluate how the survey method affected landslide frequency per unit area (LS/ha) and amount of mobilised debris (m^3/ha). Second, the experimental design was made more complex (two-way ANOVA-like tests) so that the location effect (Sisters vs. East Cap) on survey capability could be incorporated.

We took advantage of replications. The greater the number of replications, the larger the number of degrees of freedom in the error term and the smaller the experimental error, which represents the unexplained variability of the dependent variable. Two-way layouts possess a greater explanatory power than one-way analyses as they incorporate both factors (location and survey type) over the entire database. In this way, treatment interactions can be evaluated, and unexplained variability (experimental error) is minimised.

Table 2
Land use areas in East Cap and Sisters Creeks

Land use	East Cap Creek (ha)	Sisters Creek (ha)
Old growth (undisturbed)	409.3 (61.3%)	271 (44.1%)
Old growth (including fire)	578.8 (86.6%)	345.1 (56.1%)
Old harvesting	0 (0)	261.3 (42.5%)
Recent harvesting	89.2 (13.4%)	8.6 (1.4%)
Fire	169.5 (25.3%)	74.1 (12%)
Total surveyed	668	615

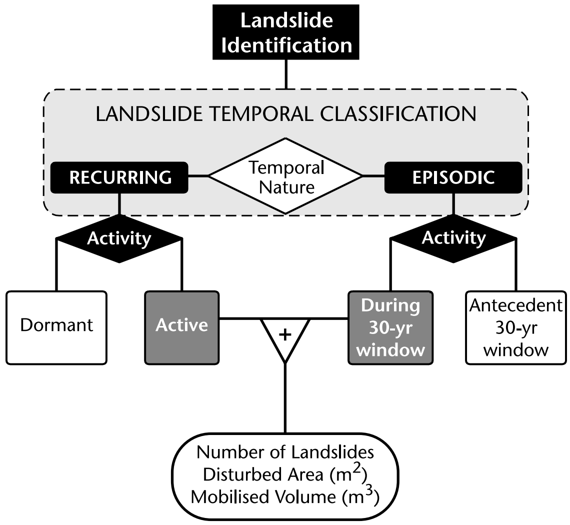

Fig. 4. The 30-year window framework adopted to obtain the quantitative database of landslides.

However, the assumptions of ANOVA were not all met. The assumptions of normality of distributions and homogeneity of variances are not satisfied. For this reason, two one-way nonparametric methods (Kruskal–Wallis and Median tests) were added (Table 3). The Median test is regarded as the most appropriate of the three options presented as it is particularly useful where the scale contains artificial limits and many cases fall at either extreme of the scale. In this study, more than 50% of observations (polygons) have a value of zero (no landslides).

3.3. GIS-based analysis

GIS technology has been intensively used in landslide studies as a tool for modelling and mapping landslide hazard (e.g., Terlien et al., 1995; Carrara et al., 1999; Donati and Turrini, 2002). Here, GIS-based analysis was explored as a way of resolving the unexpected contrasts that East Cap and Sisters Creeks exhibited in terms of landslide density and denudation rate (Table 4). A 25-m gridded Digital Elevation Model (DEM) was derived from the 1:20,000 Terrain Resource Information Management (TRIM) digital maps of the Province of British Columbia.

The nature and quality of information available, ease of GIS-extraction, and power of physical explanation are the factors that determined which macroscopic variables could be extracted from the DEM. These were elevation, slope gradient, slope aspect, drainage density, and spatial partitioning of surficial materials across terrain stability classes. Elevation affects the amount of precipitation, rate of physical weathering (e.g., freeze–thaw activity and magnitude and persistence of snow cover), and the hydrologic regime of a basin. Slope gradient is one of the most important geomorphic factors for shallow mass movement processes (Sidle et al., 1985). Slope gradient (β) appears in the Mohr–Coulomb equation (Eq. (1), infinite slope analysis' case) and directly affects both normal (σ) and tangential (τ) components of the shear stress:

$$S = C + \Delta C + (\sigma - \mu)\tan\phi' \qquad (1)$$

where μ is the pore water pressure, C is the effective soil cohesion, ΔC is the cohesion caused by root systems, and ϕ' is the angle of shearing resistance. Slope aspect influences terrain exposure to storm fronts. It also affects fluctuations of pore water pressure (μ) and alternation of weathering environment (oxidising/reducing) brought on by wet/dry and/or freeze/thaw cycles. Increase in pore water pressure alters slope stability by reducing the effective normal stress and thus soil shear strength. Comparisons of elevation, slope gradient, and aspect between the two creeks were made by inspecting both the average values and the DEM cell frequency distributions.

Drainage density (Dd) describes the degree of topographic dissection of the landscape. It is defined by the ratio between the total length of the channel network and its drainage area. Specifically, in mountainous areas of coastal British Columbia, a greater Dd corresponds with a higher number of zero- and first-order streams (gullies), ephemeral streams that naturally experience recurrent failures (i.e., debris flows/torrents) on a decennial time scale. Therefore, higher Dd means higher probability of mass failure occurrence. The scale of TRIM data (1:20,000) does not capture the entire stream network. No study has yet investigated the relationship between measured (on TRIM maps) and actual Dd. The former certainly underestimates the actual Dd, but the associated error is assumed to be the same for both sub-basins. Mapped Dd was used as a proxy of the actual Dd of the field-surveyed landscape.

Table 3
Analysis of variance and nonparametric tests of landslide density and volume

(a) One-way ANOVA-like of the entire database (survey)

Factor	Dependent variable	One-way ANOVA	Kruskal–Wallis ANOVA	Median test
		Significance		
Survey	Volume (m^3/ha)	ns	0.0003	0.0001
	Number (LS/ha)	0.002	0.0000	0.0000

(b) Two-way ANOVA-like of the entire database (survey–location)

Factor	Dependent variable	Full factorial experiment	Factorial experiment in a fixed block design	Friedman test
		Significance		
Survey	Volume (m^3/ha)	ns	ns	0.000
Location		0.002	0.002	n/a
Survey × location		ns	n/a	
Survey	Number (LS/ha)	0.003	0.001	n/a
Location		0.001	0.001	n/a
Survey × location		0.011	n/a	

(c) One-way ANOVA-like: Survey within locations

Factor	Location	Dependent variable	One-way ANOVA	Kruskal–Wallis ANOVA	Median test
			Significance		
Survey	Sisters	m^3/ha	ns	0.0003	0.0001
		LS/ha	0.002	0.0000	0.0001
	East Cap	m^3/ha	ns	ns	ns
		LS/ha	ns	ns	ns

The study of the spatial distribution of surficial materials across slope stability classes focused particularly on glacial deposits (or till) and post-glacial deposits (or colluvium). The former is considered to be less stable, having been deposited under subglacial, englacial or supraglacial conditions. It is therefore still adjusting to a subaerial, nonglacial environment. Conversely, colluvium deposits, products of subaerial mass movement, are arranged in more stable configurations. Typically, in each terrain polygon, the nature

Table 4
Sediment yields from landsliding and landslide densities during an ~30-year window (1968–2000) as obtained from both air-photo interpretation coupled and not coupled with detailed field survey

	Field surveyed area (ha)	Number of LS			Mobilised volume (m^3)			LS density (#LS/ha)		Annual LS density (#LS/ha/year)		Denudation[a] (m^3/ha)		Yield[b] (m^3/ha/year)	
		API[c]	Field	A&F[d]	API	Field	A&F	API	A&F	API	A&F	API	A&F	API	A&F
East Cap Creek	668.4	14 (41.2%)	20 (58.8%)	34	7869 (95%)	412 (5%)	8281	0.021	0.051	0.0007	0.0017	11.7	12.4	.39	.41
Sisters Creek	615	20 (14.6%)	117 (85.4%)	137	52,480 (70.5%)	21,999 (29.5%)	74,479	0.033	0.223	0.0011	0.0074	85.3	121.1	2.84	4.04
Sum	1283.4	34	137	171	60,349	22,411	82,760	0.027	0.133	0.0009	0.0044	46.9	64.5	1.56	2.15

[a] Denudation = mobilised volume/surveyed area.
[b] Yield=(mobilised volume/surveyed area)/time window.
[c] API = Air-photo interpretation.
[d] A&F = Air-photo coupled with fieldwork.

and ratios of relative abundance of surficial materials are reported (British Columbia Ministry of Environment, 2002). The analysis aimed to transform that ratio-like information into a quantitative format. To achieve this, the area of each polygon was subdivided according to the relative abundance indicated on the polygon label. After computing the areas covered by each material category (i.e., M, C, R, /CM) in every polygon, these areas were summed according to their stability class label (i.e., III, IV, and V) and the relevant histograms were plotted.

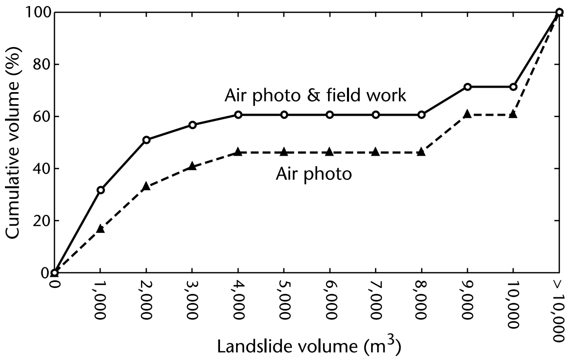

Fig. 6. Cumulative volume distributions of landslides in the ground-surveyed areas obtained by API and field-coupled API.

4. Results

4.1. Landslide visibility and implications

Fig. 5A and B reports areas of visible (from air photo) and "not visible" landslides that were measured during field survey in, respectively, recent cut-blocks (logged < 15 years ago) and forests older than 50 years. The maximum area of a "not visible" landslide scar in recent openings is about 150 m^2 (Fig. 5A), but note the gap between the largest "not visible" scar (150 m^2) and the smallest visible scar (275 m^2). This is due to the small number of observations ($n = 15$), and the critical area for visibility lies somewhere between these two values.

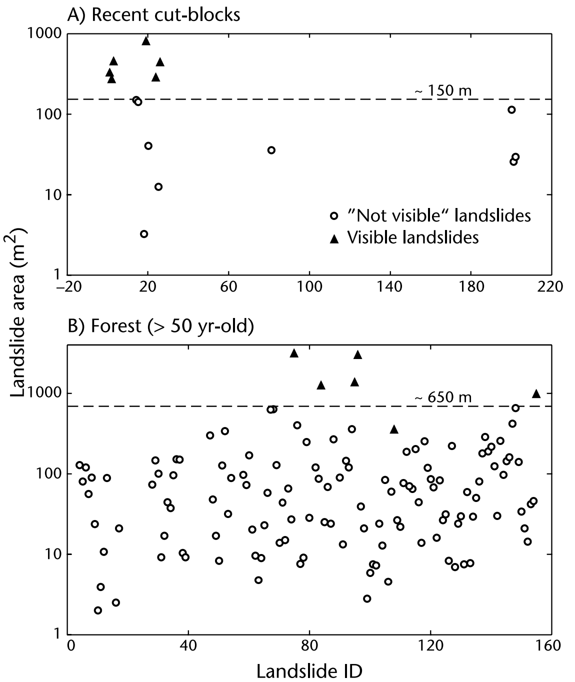

Fig. 5. Landslide visibility in relation to landslide area (initiation plus transportation zone) in (A) recently harvested cut-blocks and (B) forests older than 50 years.

In forests older than 50 years, the largest landslide scar not detected during API has an area of about 650 m^2 (Fig. 5B). One landslide smaller than this (350 m^2) was identified on an air photo; this exemplifies how the issue of landslide visibility involves various factors, such as topographic location and landscape dissection, other than land use. As a first practical application, then, if one wishes to perform an unbiased (although incomplete) air-photo-based comparison in this area between managed and wild forest, one should consider only failures that are> 650 m^2.

Inevitably, landslides missed during API produce a supplementary amount of sediment. The plotting of the cumulative percent volumes against landslide volume (Fig. 6) shows that additional amounts of debris inventoried by means of fieldwork in East Cap and Sisters Creeks range from 10% to 18% among volume classes. This is clear evidence that "not-visible" failures do contribute significant volumes of debris to the amount of mobilised material already detected on air photos.

An important supplementary question is whether missed events contributed significantly to the sediment loading of montane stream channels. This aspect has clear management implications in terms of water quality (e.g., in the Capilano Reservoir) and fish habitat; and it is also important for estimating the error associated with remotely sensed sediment budgets. Landslides have been classified as stream-connected, gully-connected, and not connected, depending on whether debris was delivered to a permanent stream, to a gully, or remained in an unchannelled portion of the landscape. According to the field data, about 58% of the mobilised volume (Fig. 7B) enters the channel network directly; and 35% is delivered to gullies and most probably will be evacuated to the stream network via debris torrent in a decennial time scale (from 10 to 40 years, cf. Thurber Engineering, 1996). However, API indicated that only 3.2% of the mobilised volumes were delivered to gullies, and here lies the highest discrepancy between air-photo and field data. The implication is that most of the small failures are connected to the drainage network. From a process perspective, this finding elucidates the real degree of geomorphic coupling of montane streams; and from an applied perspective, it shows that the rate of sediment in-filling of the Capilano Reservoir has been underestimated.

The combined effect of fieldwork and air-photo-inventory was to increase the percentage of gully-connected failures and the associated mobilised volume by about four times (from 8.8% to 32.2% and from 3.2% to 11.8%, Fig. 7A and B). The proportion of stream-connected failures decreased by nearly one-third, and the mobilised volume decreased only 5.5%. Percentage of unconnected slides showed minor changes. Integrating field with air-photo measurements, 72.6% of mobilised volumes (Fig. 7B) were delivered to the stream channels. In other words, 49% of "not visible" events were connected to stream channels and 38% to gullies (Fig. 7A). The gully network appears to have been very stable in the last 30 years. Only the formation of one new gully (scoured

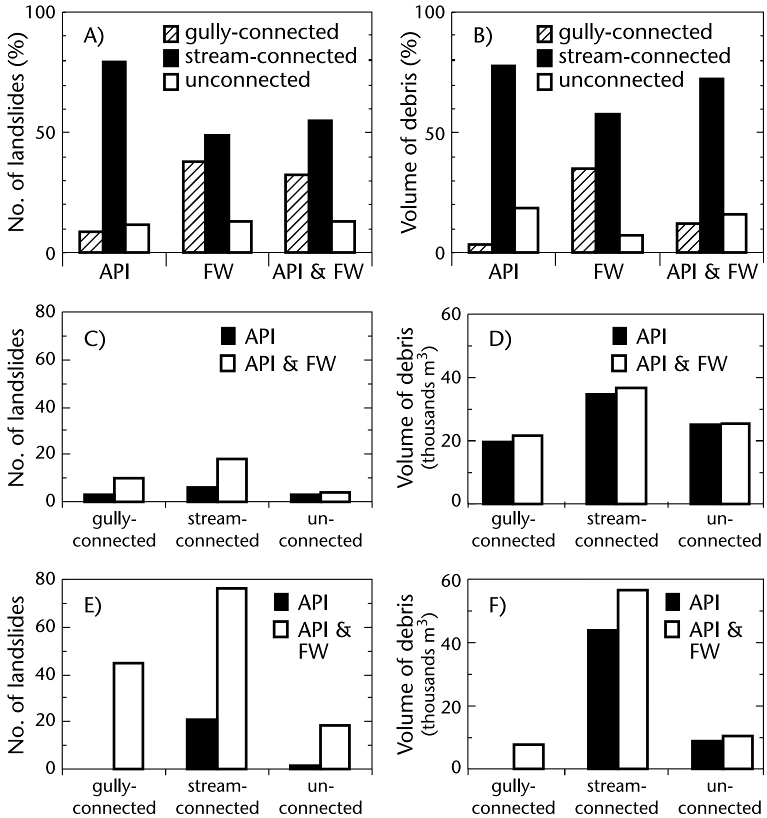

Fig. 7. Sediment delivery to streams as obtained by air-photo interpretation (API), fieldwork (FW), and field-coupled air-photo interpretation (API and FW). Lumped data for East Cap and Sisters Creeks are reported in percentages (A and B). Data for East Cap Creek (C and D) and for Sisters Creek (E and F) are reported in numbers.

down to bedrock by a large debris flow) was recorded in November 1990 in Sisters Creek. Gullies constitute preferential locations for sediment detachment (sidewall and headwall debris slides).

4.2. Interbasin variability

Results and observations on landslide sediment production deserve a more in-depth analysis; in particular, we need to see whether the lumped database of East Cap and Sisters Creeks hides any spatial variability that might prevent such findings from being generalised to the regional scale. We also seek to determine whether field surveys lead to comparable improvements of landslide identification in the two subareas and whether sediment production and sediment delivery to streams are homogeneous between basins.

The contribution of field-detected failures to the total number of landslides and, more importantly, to the total volume of mobilised debris differs greatly between the two sub-basins (Table 4). In East Cap, the number of "not visible" slides accounts for 58.8% of the total, and the associated amount of debris mobilised constitutes only 5%. Conversely, in Sisters, "not visible" events represent 85.4% of the slides identified and mobilise 29.5% of the total debris volume. When landslide densities and denudation rates are computed separately for East Cap and Sisters Creeks, they show a one order of magnitude difference. Landslide density is 0.051 #LS/ha in East Cap and 0.223 #LS/ha in Sisters, denudation rates are (respectively) 12.4 and 121.1 m^3/ha. These results demonstrate how large an interbasin variability of landslide activity exists in the Capilano watershed and, indirectly, illustrate how inappropriate it would be to generalise such figures over this physiographic region (for explanation of interbasin variability, see Section 4.5).

Denudation rates and landslide densities, obtained solely from air photos (Table 4), are lower than those obtained by coupling intensive fieldwork. The ratio between the two types of survey varies with location and with the dependent variable considered: higher in Sisters Creek, lower in East Cap Creek, higher for denudation rates, lower for landslide densities (Table 5). Also, the Sisters–East Cap ratio increases when one couples fieldwork to the routine inventory method (API). The highest survey ratio is in Sisters Creek for landslide density (about 7), while the highest Sisters–East Cap ratios are recorded for denudation (7.3 with air photo and nearly 10 with field-coupled remote survey).

Table 5
Denudation and landslide (LS) density ratios

	A&F/API		Sisters Creek/East Cap Creek	
	East Cap Creek	Sisters Creek	API	A&F
LS density and annual LS density	2.4	6.8	1.6	4.4
Denudation and yield	1.05	1.42	7.3	9.8

A marked interbasin variability was also found in terms of landslide sediment delivery to streams. In East Cap Creek, the proportions between the stream gully and not-connected failures do not vary substantially between API and field-coupled API (Fig. 7C and D). By contrast, in Sisters Creek, no gully-connected failures were detected from API. When field-detected failures were added, gully-connected failures accounted for 45% of the total events identified, and 10.3% of the volume of debris mobilised (Fig. 7E and F).

4.3. ANOVA and nonparametrics

To this point, we have commented on the general trends obtained from the lumping of the entire database or, at best, split into the two tributary domains. A more thorough analysis of spatial variability can be made by means of ANOVA and its corresponding nonparametric tests. The two types of surveys are significantly different for both dependent variables (volume and number of landslides) at the 0.01 level (Table 3a). The only exception is the one-way ANOVA for volumes of mobilised debris. The large differences in landslide densities and mobilised volumes of debris described between the two sub-basins (locations) have prompted us to handle locations as fixed blocks. Blocking was justified for both dependent variables, as landslide density and mobilised volumes varied significantly as a function of location (Table 3b). A fixed block design, when blocking is used to increase precision of comparisons, assumes no block-by-treatment interaction (i.e., location-by-survey), while such interaction is of primary interest when blocking is used to broaden the scope of inference (León and Mee, 2000).

As for the full factorial experiment, the advantage of having a factorial arrangement of treatments (or factors) over a block design lies in that one can analyse interactions and, where interactions are not statistically significant, one can reduce the number of treatment means in the multiple comparison test. According to the full factorial ANOVA (Table 3b), the interaction is significant for landslide density. Therefore, no comment can be made on locations or survey separately; instead, having detected the significant interaction, its meaning has to be graphically evaluated by inspecting the plot of the means (Fig. 8A and B). The plots show that the coupling of API with intensive fieldwork has sensibly increased average values of landslide density and volumes in Sisters Creek. In East Cap Creek, such increase appears to be negligible. This difference between the two locations is particularly large in terms of landslide density (significant location-by-survey interaction).

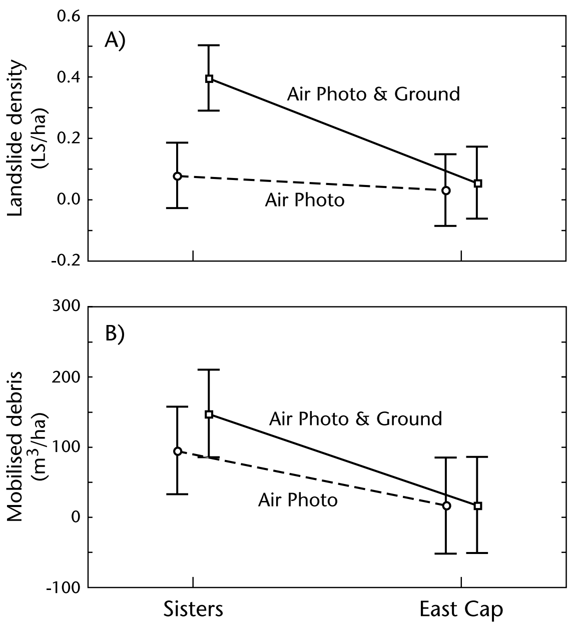

Fig. 8. Survey–Location interaction of (A) landslide density and (B) mobilised debris. Bars indicate standard errors of the mean.

As for the volumes of debris per hectare (m^3/ha), they show no significant survey-by-location interaction; hence, one can comment on survey and location separately. The former is not significant; the latter is (Table 3b) with Sisters greater than East Cap. The nonparametric equivalent of a two-way ANOVA, the Friedman test, requires the same assumptions as the fixed block design (i.e., null survey–location interaction); and, as such, it can be performed only on mobilised volumes of debris (Table 3b). The test indicates that at least one of the survey–location combinations is different from the others; this is the field-coupled API conducted in Sisters Creek.

We performed the Tukey's Honest Significant Difference (HSD, a generalisation of Tukey's test for unequal sample sizes) multiple comparison test, which is considered to be of intermediate conservatism. The test, in line with the Friedman's results, reports that the coupling of API with intensive fieldwork in Sisters Creek gives a significantly greater amount of mobilised debris per unit area (m^3/ha) than does any other survey–location combination. This result stresses the importance of conducting fieldwork in the Sisters Creek area.

The database was then split in two location-wise; hence a series of one-way ANOVA-like tests was performed. Regardless of the dependent variable examined, in East Cap, survey types were not significantly different (K–W and Median tests); conversely, in Sisters Creek field-coupled survey was significantly greater than the air-photo-based survey (Table 3c).

4.4. Survey influence on effects of forest management

Moving on to the anthropogenic impacts, the comparison of the management effects between air-photo-based and field-coupled surveys (Table 6) showed minor differences. Fieldwork had the effect of shifting the old-logging–old-growth ratio toward unity (no acceleration for both dependent variables). According to air-photo-derived data, recent logging produced an acceleration factor of 5.2 (in terms of landsliding rate—LS/ha/year) as opposed to 2.1 obtained by the field-coupled survey; the effect of recent logging on denudation rates remained the same between survey methods. Globally, as a result of fieldwork, absolute numbers change but acceleration

Table 6
Management effects on rates of landsliding and denudation: comparison between air-photo-based and field-coupled landslide inventories

	Land use	Annual LS density (#LS/ha^{-1}/year^{-1})		Yield (m^3/ha^{-1}/year^{-1})		Management effects Annual LS density (#LS/ha^{-1}/year^{-1})		Yield (m^3/ha^{-1}/year^{-1})	
		API	A&F	API	A&F	API	A&F	API	A&F
Sisters Creek	Undisturbed forest	0.0023	0.0093	1.92	3.49	1.0	1.0	1.0	1.0
	Old logging	0.0005	0.0052	0.66	2.59	0.2	0.6	0.3	0.7
East Cap Creek	Undisturbed forest	0.0005	0.0016	0.33	0.34	1.0	1.0	1.0	1.0
	Recent logging	0.0026	0.0034	1.46	1.53	5.2	2.1	4.4	4.5

factors remain fairly constant (Table 6). From the land manager's perspective, fieldwork application does not change the situation; on the other hand, fieldwork provides the geomorphologist with better sediment source data to construct a more realistic sediment budget.

4.5. GIS as a tool for explaining interbasin variability of landslide density and sediment yield

In seeking a qualitative explanation for the one order of magnitude difference in landslide denudation rates between the two study areas, a GIS-based topographic analysis was performed. Elevation, slope gradient, slope aspect, drainage density, and spatial partition of surficial materials across terrain stability classes are the variables that were considered.

East Cap Creek is located at a significantly higher elevation (832 m $\pm$ 2) than Sisters Creek (664 m $\pm$ 2). Accordingly, maximum frequency was reached at the 600–800-m category in Sisters, whereas elevation frequency peaked at the 1000–1200-m category in East Cap Creek (Fig. 9A). Higher elevation might have slightly contributed to a faster evacuation of glacial till deposits from East Cap upper- and mid-slope locations, as higher elevation induces higher precipitation and greater sediment transport.

Average slope in Sisters Creek is significantly higher ($31.1° \pm 0.1$) than in East Cap Creek ($28.1° \pm 0.1$). Although it is difficult to generalise about a critical slope gradient for slope failure, it is reasonable to assert that terrain with slopes over 35° can be regarded as shallow, mass movement prone, when soil is present (Sidle et al., 1985). Data from Howe Sound and Chapman Creek, located in the same physiographic region, indicate a critical gradient for sliding of about 30° to 35° in cut-blocks and of 35° to 40° in forested terrain, and landslide initiation was found very unusual below such values (Brardinoni et al., 2002). Percentages of slope steeper than 35° are significantly different (Z-test), with Sisters Creek having 34% of DEM cells with slope gradient steeper than 35° and East Cap Creek only 19.5%.

The influence of slope aspect on landsliding deserves particular attention; several studies have examined this issue in the study area. Approximately 75% of the landslides inventoried by O'Loughlin (1972) in Howe Sound, Capilano watershed, and Seymour watershed exhibited a southerly aspect. He justified such landslide preferential orientation by noting that "north-facing slopes are rocky and broken, a condition which discourages landslide formation, while south-facing slopes are relatively uniform and underlain by an extensive unweathered till substratum" (p. 31). This spatial arrangement of surficial materials is likely to derive from the north-to-south flow that characterised the movement of Pleistocene ice sheets in the Pacific Ranges (Armstrong and Brown, 1954). Relations between surficial materials and aspect have been investigated more systematically for the entire Capilano watershed (Greater Vancouver Regional District, 1999). They confirmed that rock dominates northerly aspects; and colluvium and till are most extensive on west-, south-, and east-facing aspects.

Heaviest rains in the Pacific Ranges are brought by southwesterly air flows; south- and west-facing slopes are therefore more directly exposed; north exposures are likely to remain more uniformly damp; and alternation of wet/dry cycles is enhanced on south-facing slopes. In light of these climatic controls, south- and west-oriented slopes would be expected to be more favourable for landsliding. Fig. 9C shows that south-facing slopes are of comparable extent in East Cap and Sisters Creeks but that west-facing slopes are

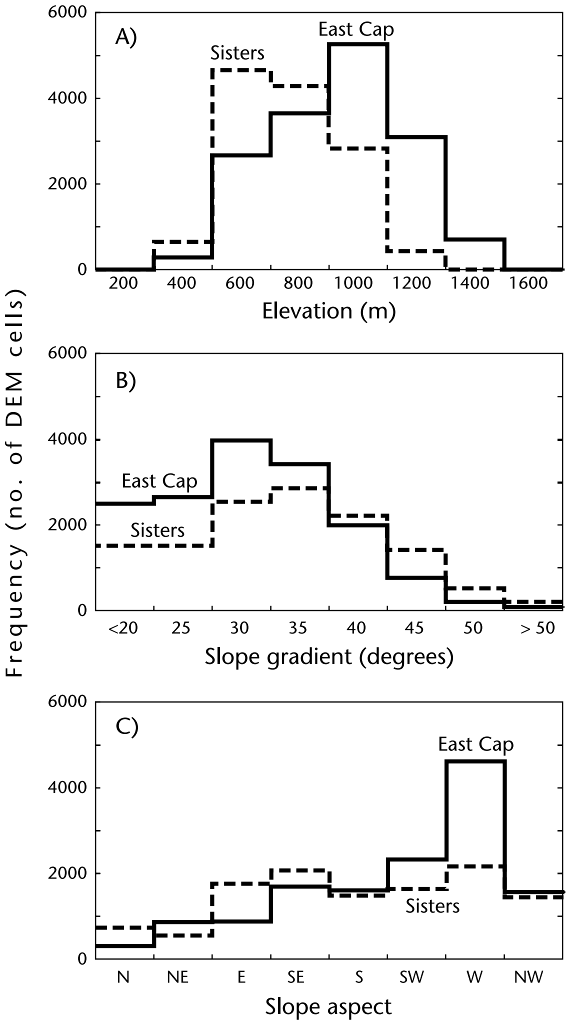

Fig. 9. Frequency distributions of (A) elevation, (B) slope gradient, and (C) slope aspects of East Cap and Sisters Creeks.

more abundant in East Cap Creek. East Cap Creek should, therefore, be more susceptible to landsliding than Sisters Creek. The evidence, however, is that landslides appear to be slightly more abundant on south and east orientations (Greater Vancouver Regional District, 1999). Thus, unlikely aspect plays a significant causal role for landsliding in the watershed.

Drainage density of the field-surveyed sites is greater in Sisters Creek (3.6 km^2/km) than in East Cap Creek (2.2 km^2/km), partly explaining the greater denudation rate for the former substudy area.

In terms of the spatial distribution of surficial materials throughout stability classes (Fig. 10A and B), two main points can be made. First, in Sisters Creek, class V cover is dominant; in East Cap Creek, class IV covers the majority of the land. Thus, the B.C. terrain stability classes are consistent with the outlined discrepancies in denudation rates. Second, if one considers only class V (unstable) polygons, colluvium (C) and bedrock (R) cover almost the same area in the two regions. However, till deposits (M) in Sisters Creek cover an area that is more than double the till-mantled terrain in East Cap Creek. In addition, there are nearly 0.2 km^2 of terrain where colluvium partially covers underlying till (/CM), a configuration that can be considered as unstable as till itself.

Briefly summarising, the higher denudation rate from landsliding in Sisters Creek can be explained by considering that such a sub-basin possesses (i) steeper slopes: 34% steeper than 35°, whereas in East Cap Creek, only 20% of the terrain is steeper than 35°; (ii) major till on class V slopes: it covers a surface of 2 km^2 in Sisters Creek vs. just 0.7 km^2 in East Cap Creek; and

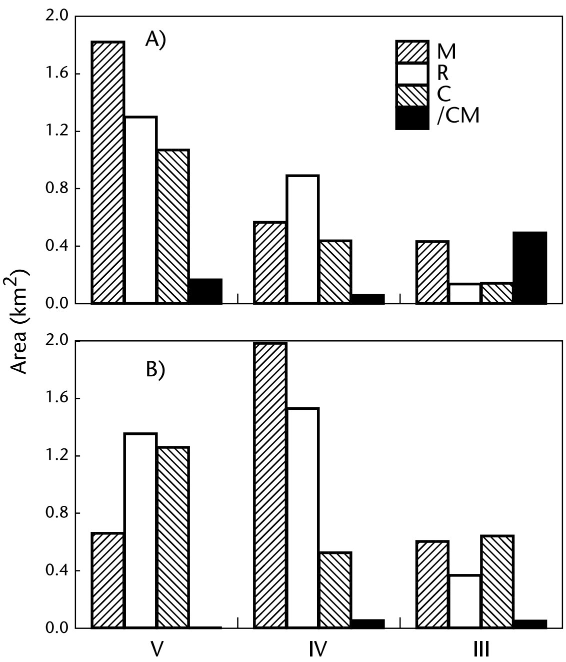

Fig. 10. Distributions of surficial materials: (A) in Sisters Creek and (B) in East Cap Creek. Histograms reports bedrock (R), colluvium (C), glacial deposits (M), and glacial deposits partially covered by colluvium (/CM).

(iii) higher drainage density: 3.6 km/km^2 in Sisters Creek compared to 2.2 km/km^2 in East Cap Creek.

5. Discussion

Estimation of the maximum size of undetectable landslide scars on air photos is of fundamental importance for both scientists and forest managers. Nevertheless, little research has addressed the topic (e.g., Robison et al., 1999); this could be due to underestimation of the relative importance of small failures and to the physical- and cost-prohibitive requirements of fieldwork.

In Fig. 11, we summarised the factors that have been identified to affect landslide visibility during API. Factors that are manifestly related to the quality of photography itself [such as nominal scale, sensor type (colour, black and white, etc.), weather conditions (snow cover, clouds)] are not included. Relatively large failures that frequently were not detected in antecedent API were generally located on the lower portion of very steep (>40°) old-growth forested slopes. Due to the progressive downhill increase of pore water pressure, clusters of debris slides are often found in these locations. On recently harvested cutblocks, the problem in detecting slides lies in the shallow nature of the events, which facilitates a very fast process of revegetation. Furthermore, gully-related failures connected to permanent streams are more difficult to detect. This is because stream-connected failures have their deposition zone (e.g., flow fans) readily washed out by the stream they have impacted.

Analysis of landslide density and denudation rates was tackled by considering two main factors affecting mass failure detection: type of survey and location. The former is external to the analysed system, and the latter is an intrinsic property and can be regarded as the spatial heterogeneity of the system's propensity to fail. Intensive ground checking of the study areas has shown that "not visible" landslides accounted for about one-third of the total volume of debris mobilised via mass movements during the last 30 years. Even more interestingly, the two subwatersheds exhibited very different rates of sediment production from landsliding (about one order of magnitude discrepancy), with Sisters Creek being the more active (Table 4). Although these two Capilano River tributaries possess many similar biophysical characteristics, they behave in strikingly different ways.

The overall survey-by-location picture can be summarised by saying that the same treatment (survey type) performed differently in different locations (blocks). Field-coupled surveys exhibited significantly greater landslide densities and denudation in Sisters Creek. The same variables in East Cap Creek were shown to be rather indifferent to the conduct of fieldwork as a supplement to API, thus confirming the simple counts. Friedman's test showed that field-coupled API in Sisters Creek gives significantly greater mobilised volumes than any other survey–location combination did. This finding emphasises the importance of intensive ground checking. Solely from air photos, landslide sediment production in East Cap and Sisters Creeks would have not been significantly different. Apparently, some types of forested terrain hide important numbers of "not visible" land-

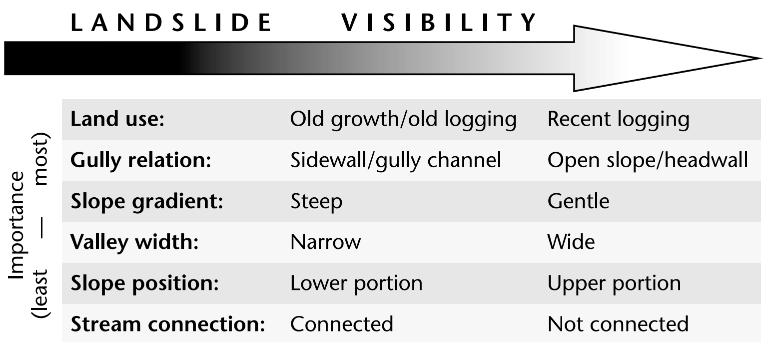

Fig. 11. Ranking of factors affecting landslide visibility on aerial photographs.

slides, while others do not. In other words, the issue of "not visible" events can be complex even within a "medium-size" drainage basin. This finding has important practical implications: in East Cap-like areas, fieldwork is practically unnecessary and sediment budget evaluation requires virtually no correction factor to account for not visible events. Conversely, Sisters-like areas require intensive fieldwork in order to evaluate the "invisible" volume of mobilised debris.

One aspect to consider in comparing fieldwork landslide detection efficiency is the relative abundance of different land use cover—in our case, the relative extent of old-growth, old-logged, and recently logged areas. In Sisters, the presence of a large portion of old harvested terrain and only a small area of recently harvested cut-blocks (Table 2) does not favour landslide detection from air photos. Conversely, the absence of the old-logging land use category and the large, recently developed clearcut areas aid remote recognition of mass failures in East Cap (Table 2). We consider historic fires to have no effect on landslide visibility; canopy height in fire-affected forests was comparable to that in old-logged and old-growth forested terrain.

A last benefit of conducting intensive fieldwork is the recognition that gully-related events have a greater importance than one could expect from API. They constitute more than one-third (both in terms of number of events and of mobilised volumes) of the "missed" events, while from air photos alone, they accounted for just below 10% of the total number of failures and volumes. From aerial photos and field traversing of Sisters and East Cap Creeks, the gully network appears to have been very stable in the last 30 years. The stream channel network functions as a preferential transportation pathway for debris flows/torrents through the landscape. Unconnected failures account for relatively low percentages (< 16%) of the total number and volume of landslides (see Fig. 7). In this mountain environment, the drainage network is extremely efficient in evacuating the sediment load. This efficiency is achieved through alternation of a "normal fluvial regime," where supply-limited amounts of small material systematically are eroded from the stream channel, and of a "catastrophic regime," which entails removal of large quantities of sediment and woody debris via debris flows/torrents (Nistor, 1996).

One of the main issues that puts air-photo-based landslide studies under suspicion is the relative bias introduced (because of different conditions of visibility) when one compares mass wasting activity in logged and undisturbed terrain. This case study has shown that the discrepancies between air-photo-based and field-coupled surveys (Table 6) have relatively slight management implications. Fieldwork has the effect of shifting the old-logging–old-growth ratio from negative accelerations to near constancy. Management effects of recent logging on denudation rates remained constant survey-wise, while landsliding ratios exhibited a three-time decrease as a result of fieldwork coupling. This is due to the higher number of "hidden" slides in old-growth forest than in recent cut-blocks, whereas canopies of old-logged and old-growth forests have a similar effect on landslide visibility.

In order to explain the large discrepancy in denudation rate that was found between the two creeks, we performed a GIS analysis. The outcome depicted Sisters and East Cap basins as two contrasting geomorphic environments (Fig. 3A and B). Several physiographic characteristics make Sisters basin a highly landslide-prone environment. This includes steep slopes (one-third >35°), and till-mantled slopes (~ 40% class V) are a large source of potential non-coherent material. Also, high drainage density allows efficient evacuation of the sediment load brought into the channel network via sidewall debris slides and windthrow. Conversely, in East Cap, slopes are generally gentler; till is mainly located on less steep polygons (class IV); and drainage density is significantly lower, thus imparting a lower connectivity to the system.

These observations are in accordance with the framework that subdivides systems into weathering- and transport-limited systems (also termed supply-limited and -unlimited) (Carson and Kirkby, 1972). In the first case, the limiting factor is sediment production; in the other, sediment mobilisation. In the mountainous, forested environment of coastal British Columbia, transport-limited basins typically have a high density of headwater channels incised into thick glacial drift or closely jointed bedrock. This ensures virtually unlimited debris supply, in addition to many unstable trigger points for debris slides and flows. Supply-limited basins denote slower recharge rates and fewer zones of instability. This is usually due to more massive bedrock or a thinner cover of glacial drift (Bovis and Jakob, 1999). In this sense, East Cap and Sisters Creeks seem to be good examples of supply-limited and transport-limited basins, respectively (Fig. 3A and B).

6. Conclusions

(i) This study provided for the first time a systematic examination of the assumption that the relation between the numbers of landslides detectable from air-photo inventories and ground surveys is the same as that for landslides that are "non-visible" on air photos. In the Capilano River basin, the number of slope failures that remained undetected from air photos and the relative volume of debris mobilised showed great sub-basin variability. In basins like Sisters Creek, where below threshold scale failures are disproportionately extensive, the forest canopy does hide an important population of "not visible" landslides; in others, such as the East Cap Creek basin, it does not. It follows that, if one wants to obtain complete information for sediment budget evaluation and terrain stability assessment, supplementary fieldwork is mandatory in Sisters Creek-like areas. In East Cap Creek-like areas, the supplementary fieldwork would not be justifiable.

(ii) Maximum area of "not visible" failures in forest older than 50 years was 650 m^2, larger than what has been assumed in previous studies. In recently harvested cut-blocks, the value dropped to about 150 m^2. Factors that have proven to affect landslide visibility were land use, gully relation of failure, slope gradient, valley width, slope position, and stream connection. Lower portions of steep, old-growth forested slopes located in narrow valleys are most likely to hide a relevant number of slope failures.

(iii) Fieldwork has demonstrated that gully-related events have a greater importance than one could detect from API. They constitute more than one-third of the missed events, while from air photos, they accounted for $<10\%$.

(iv) This case study has demonstrated that forest management effects, as perceived between air-photo-based and field-coupled surveys, vary very little. The impact of recent logging on denudation rates remained constant survey-wise: landsliding ratios exhibited a three-time decrease as a result of fieldwork coupling because of the higher number of "invisible" slides in old-growth forest. Canopies of forest logged more than 50 years ago and those of undisturbed forest have a similar effect on landslide visibility.

(v) Large differences between Sisters and East Cap Creeks in landslide density and denudation rates were qualitatively explained via GIS-based topographic analysis. The outcome depicted the two sub-basins as contrasting geomorphic environments. Accordingly, the different landslide activity between the study areas was clarified with reference to the distinction between supply-limited (i.e., East Cap Creek) and transport-limited (i.e., Sisters Creek) basins.

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