The sediment budget in severely disturbed watersheds, Queen Charlotte Ranges, British Columbia

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Sediment budgets, averaged over one or more decades, have been estimated for four small (3.9 to 12.6 km^2) drainage basins in the Queen Charlotte Islands for periods before and after clear-cut logging of 10 to 20% of the area, including stream banks. Data were obtained by field and photogrammetric measurements of sediment deposits supplemented by regional rate estimates for minor erosional processes. Landslides, riparian erosion, and soil creep are important sediment sources before logging, the former two dominating. Sediment production on hillslopes and delivery to stream channels may increase following logging, but not invariably. In each of the study basins, significant stream bank erosion following logging resulted in the accumulation of a substantial "wedge" of coarse sediment in the stream channel. Sediment transport through the channels has increased by up to 10 times; however, the residence time for the greatly increased volume of in-channel sediment has increased by up to 100 times. The in-stream sediment wedges are areas of persistently poor aquatic habitat. Their development was associated with obsolescent logging practices and they remain atypical.

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Des quantités de sédiments mis en place sur une durée moyenne de 10 ans ou plus, ont été estimées pour quatre petits bassins de drainage (3,9 à 12,6 km^2) dans les Îles de la Reine Charlotte, pour des périodes qui précèdent ou suivent des coupes totales sur 10 à 20% des superficies de ces bassins, y compris les berges des cours d'eau. Les données furent obtenues par des mesures faites sur le terrain et à l'aide de procédés photogrammétriques, mesures complétées par des taux estimés à l'échelle régionale pour les processus d'érosion mineurs. Les éboulements, l'érosion riparienne et la reptation sont des sources importantes de sédiments avant la coupe, les deux derniers processus étant prédominants. La production de sédiments sur les versants et leur transport vers le lit des cours d'eau peut augmenter après la coupe, mais pas nécessairement. Dans chacun des bassins étudiés, une érosion importante des berges après la coupe entraîne l'accumulation d'un amas important de sédiments grossiers dans le lit des cours d'eau. Les quantités de sédiments transportés dans les cours d'eau ont augmenté jusqu'à 10 fois; cependant, la durée du séjour au même endroit des sédiments dans le lit du cours d'eau a été augmentée jusqu'à 100 fois, là où les volumes avaient été fortement accrus. Les accumulations de sédiments grossiers constituent des habitats aquatiques définitivement pauvres. Leur développement fût relié à des pratiques de coupe révolues et elles demeurent atypiques.

[Traduit par la revue]

Introduction

In the mountains of the Queen Charlotte Islands, soil erosion on hillslopes and sedimentation in streams have been accelerated by timber harvesting activities. In most respects, the environment and processes of sediment transfer are similar to those in adjacent southern coastal Alaska (see Swanston 1969, 1974). Debris slides are common in shallow soils developed on till and colluvium on steep hillsides and in road sidecast. A substantial number of the slides run directly into stream channels; many propagate into fluid "debris torrents" (Swanston and Swanson 1976; Miles and Kellerhals 1981) in steep, headwater gullies, and may then move into channels of relatively low gradient (5–7°). Disturbance of the stream channel, either by delivery of high volumes of sediment or by direct human interference, may trigger further fluvial erosion and sediment transport. The effects upon aquatic habitat may be substantial and persistent. The same processes, of course, occur naturally.

For land management purposes, it is useful to know the significance of the prominent but episodic debris slides in comparison with other modes of sediment transfer (see Fig. 1), what proportion of sediment mobilized on hillslopes is delivered to stream channels, how different are sediment transfers in "undisturbed" and "disturbed" terrain, and how persistent are the effects of sediment movements, particularly in stream channels.

For this study, we have investigated four small watersheds in the Queen Charlotte Ranges (see Fig. 2) that exhibit severely disturbed stream channels. The middle and downstream reaches of the main stem channels contain recent accumulations of gravel, termed "sediment wedges," that are of the order of 1 km in length (see Figs. 3 and 4 for examples). The deposition zones are an order of magnitude wider than the normal channel and are bordered by severely eroded banks. All four channels were subjected to in-stream or cross-stream timber harvesting activities. Contemporary harvest regulations prohibit such practices, but these sites remain instructive examples of the persistence of extreme fluvial disturbance.

Sediment budget concepts have been applied recently to attempt to understand geomorphic processes and the effects of land management in the forested drainage basins of the Pacific Northwest (see Swanson, Janda et al. 1982). In this study, the sediment budget is constructed in terms of sediment transfers in the stream channel. Hence, the standard form

$$[1] \quad I - \Delta S = \phi$$

takes the following definitions: I is the mass or volume of sediment input across the stream bank during a specified period, Δt (and from upstream if only a limited reach of channel is being

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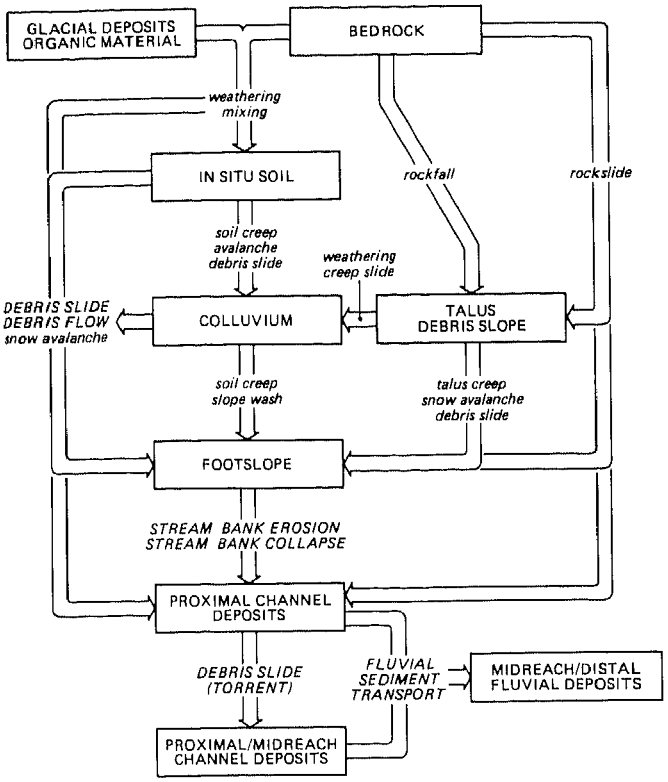

FIG. 1. Conceptual model of sediment transfer in small steepland watersheds. Boxes indicate principal reservoirs; the principal processes are in capital letters.

considered), ΔS is the change in the mass or volume of sediment stored in the channel reach in Δt (an increase is positive), and ϕ is the mass or volume of sediment output from the channel reach in Δt. However, attention is given also to sediment transfers on the hillslopes. The sediment budgets are cast over periods of 10 to 40 years, allowing some commentary upon geomorphological as well as management questions.

Environmental setting

Apart from terrain mapping for land management purposes, there has been no detailed study either of the geophysical environment in the Queen Charlotte Islands or of sediment transport or sediment yield. A combination of climatic, geologic, and physiographic factors makes the environment virtually ideal for rapid mass wasting.

The climate is perhumid marine. Annual precipitation varies from 1500 mm on the eastern plains to more than 5000 mm on some west coast slopes (Alley and Thomson 1978). Mean annual precipitation in Tasu Sound (see Fig. 2) from 1964 to 1983 was 4220 mm with roughly 70% occurring from October through March. As the Queen Charlotte Islands lie in a westerly Pacific storm track, they are subject to intense rainstorms. In Rennell Sound (see Fig. 2), storms known to have initiated mass wasting generally exceed 120 to 150 mm within a 12- to 24-h period and occur annually (Wilford and Schwab 1982). This threshold intensity falls close to Caine's (1980) limit criterion for the occurrence of shallow debris slides. Snow, ephemeral at sea level, is confined mainly to elevations above 600 m. The frequency of occurrence of destructive winds is greater in the Queen Charlotte Islands than elsewhere in Canada, with recorded gusts approaching 200 km/h (Alley and Thomson 1978).

The generalized geology of the Queen Charlotte Islands is shown in Fig. 2 and the dominant rock types in the four study watersheds are given in Table 1. These rock formations usually are well bedded, jointed, or fissured and highly susceptible to erosion (Sutherland Brown 1968). A high rate of geomorphic activity is promoted also by movements on the Queen Charlotte Fault. Between 1899 and 1974 there were 1268 earthquakes recorded for Graham Island, of which the largest was of Richter magnitude 8.0 in 1949 (Milne et al. 1978). Widespread mass wasting accompanied this event (Alley and Thomson 1978).

The most recent glaciation in the Queen Charlotte Islands ended approximately 11 000 years ago and is expressed topographically by the steep valleyside slopes. In the four study watersheds, the slopes typically are concave or straight with gradients ranging from 0.5 (25°) on the foot slopes to more than 1.7 (60°) on bedrock in the headwaters and averaging between 0.7 (35°) and 0.9 (40°) on the midslopes. The steep slopes are mantled by colluvial deposits less than 1 m thick, while the foot slopes usually are masked by colluvium and occasionally by till (e.g., Mosquito tributary creek) more than 1 m thick. The abundance of colluvium in the study watersheds and throughout the region reflects the intensity of weathering and mass wasting processes in this inherently unstable terrain.

Valley bottoms contain fluvial sands and gravels, occasionally underlain by finer textured till and overlain by coarser textured colluvium. At the mouths of Armentieres Creek and Lagins Creek, fluvial materials are underlain by deltaic and by marine deposits, respectively. In addition, several stream bank exposures along Armentieres Creek, Mountain Creek, and Lagins tributary creek contain peat deposits and buried paleosols (often as successive cumulic horizons).

Soils have a high moisture content for most of the year, resulting in Regosols, Brunisols, Ferro-Humic Podzols, or Humo-Ferric Podzols depending on their state of development. Where there is also a net accumulation of organic matter, Folisols develop in association with the Ferro-Humic Podzols (Valentine et al. 1978).

The area lies within the Coastal Western Hemlock Biogeoclimatic Zone, which is the most productive forest zone in British Columbia (Valentine et al. 1978). Sitka spruce (*Picea sitchensis* (Bong.) Carr.), western hemlock (*Tsuga heterophylla* (Raf.) Sarg.), and western red cedar (*Thuja plicata* Donn) are the main forest types, with mountain hemlock (*Tsuga mertensiana* (Bong) Carr.) and Alaska yellow cedar (*Chamaecyparis nootkatensis* (D. Don) Spach) present to a lesser extent. The Mountain Creek and Armentieres Creek watersheds lie within the wetter Coastal Cedars – Pine – Hemlock Subzone (J. Pojar, personal communication), which supports low-productivity mixtures of red and yellow cedar, western and mountain hemlock, and shore pine (*Pinus contorta* Dougl.).

Forest cover maps compiled by the British Columbia Forest Service indicate that forested slopes in the study basins support conifers more than 250 years old. Logged slopes are revegetated primarily by shrubs, herbs, bryophytes, and young conifers, while logged stream banks and valley flats support a dense cover of red alder (*Alnus rubra* Bong.) interspersed with young conifers and an understorey of shrubs and herbs.

We have, then, a situation in which exceptionally steep, tectonically active mountain slopes are developed on easily weathered rocks, with surface veneers of noncohesive recent sediments in a perhumid environment. In these circumstances, the maintenance of a continuous vegetation cover commonly is critical for continued slope stability. The binding strength of rootmats is the main effective mechanism (see discussion in Swanston, 1974). Sediment transfer is apt to be dominated by major, episodic events, such as debris slides, with substantially increased frequency following logging on steep hillsides.

Logging histories of the study watersheds are summarized in Table 1 and details are given in Roberts (1984).

Determination of sediment sources and transfer processes

In this paper, "sediment production" refers to the amount of sediment mobilized by a process on hillslopes and "sediment delivery" denotes the amount that reaches a stream channel. Rates of sediment production and delivery by various transfer processes, abstracted from published results of other studies in the Pacific Northwest, are reviewed in Roberts (1984) and summarized in Table 2; as site-specific factors cause transfer rates to vary greatly within the Pacific Northwest, a range of

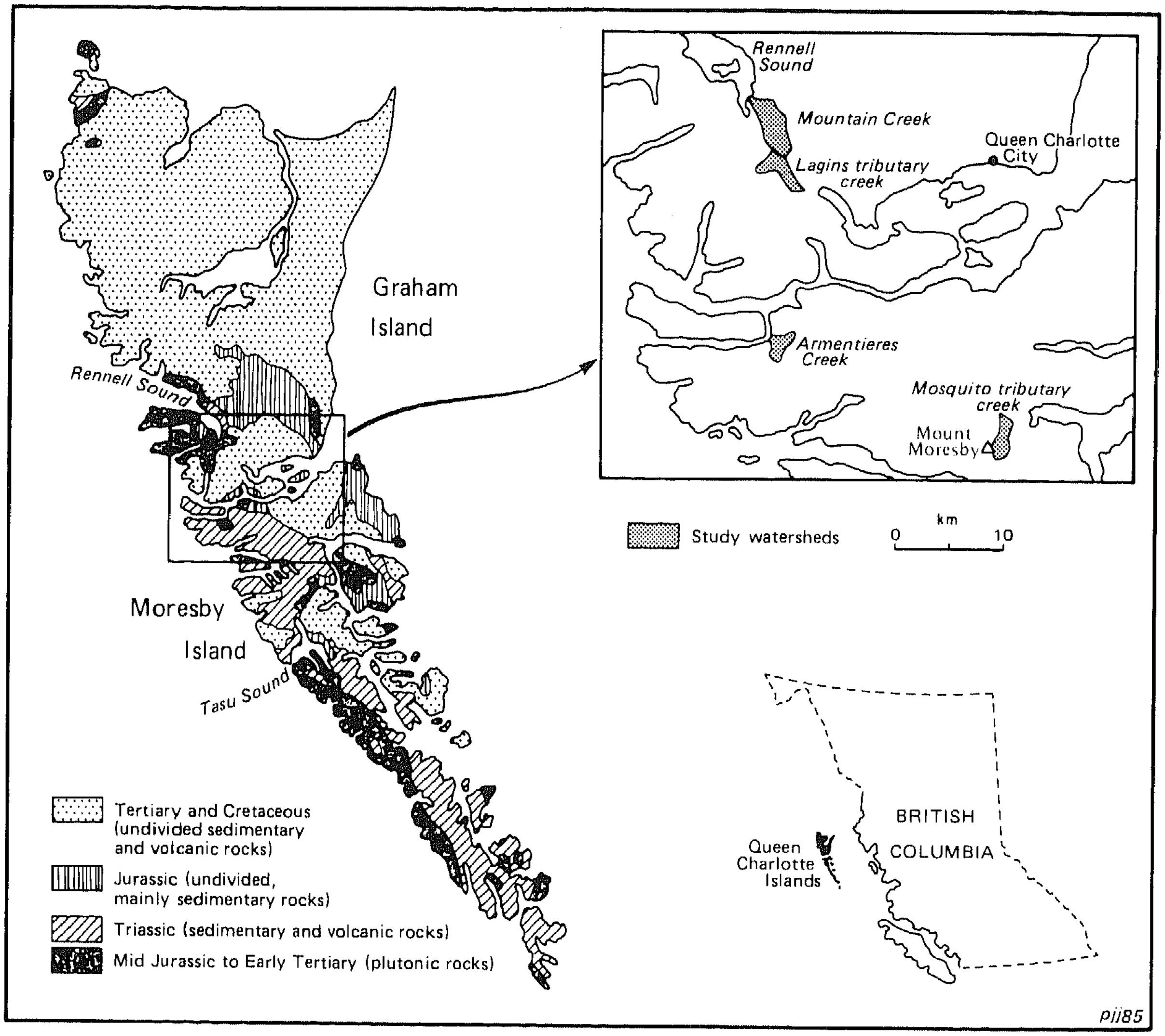

FIG. 2. Location map of study basins, including generalized geology and physiography of the Queen Charlotte Islands.

rates is given for each process. The reader still is cautioned that the implied forested–logged comparisons sometimes are based upon data from quite different groups of studies in different places that may not be closely comparable. In general, the most important processes are landslides, stream bank erosion, soil creep in logged terrain, and road surface erosion. In this paper, "landslides" is the collective term for debris slides, debris avalanches, flows, and torrents. Snow avalanches, which occur locally within the Queen Charlotte Ranges, are not considered.

From air photo and field investigations, landslides and riparian erosion also appeared to be major sediment delivery processes in the study watersheds. Hence, the mobilization of sediment by these important processes was measured from air photos. Photography of the study watersheds covers a period of exactly 50 years at scales ranging from 1 : 10 000 to 1 : 63 360.

Photogrammetric measurements of slope failures were made with a Wild A6 stereoplotter from 1 : 10 000 scale air photos flown for this project in 1982 except in the Lagins tributary Creek basin, where 1976, 1 : 15 840 scale air photos were used. Landslide scars with a surface area greater than 200 m^2 were mapped at a scale of 1:5000 and subdivided into an initiation zone where most soil erosion occurs, a depositional zone where most debris is deposited, and an intervening transport zone (not always present) through which upslope material passes and additional soil may be eroded. The length and width of each zone was measured to within ±0.5 m, while the depth of erosion was assumed to be 50 cm in the initiation zone (Smith et al. 1984, Table 1) and 25 cm in the transport zone (after Rood 1984; this reference also gives details of identification and mapping procedures). The volume of material mobilized by slope failures was calculated as the product of these dimensions and, by noting the location of deposition, the volume entering the drainage network was estimated. The approximate age of each event was established from the earlier air photos.

Erosion of stream banks was measured from air photos uncorrected for tip or tilt displacements (any such corrections would be smaller than the limit of measurement precision). The bank edges along the main stem of each creek were traced from each set of photos and redrawn to the largest common scale. The width of the stream channel was measured normal to the banks at 50-m intervals (to within ±0.8 m). Measurements were begun downstream of the most distal instream sediment wedge and extended as far upstream as photo resolution permitted (usually up to second-order channels). Changes in channel width since logging allowed the area of eroded riparian land to be calculated and a volumetric estimate was obtained by using stream bank heights measured in the field. Major width changes prior to logging were not apparent from air photos. Because of the uncertainties involved in photogrammetrically delineating forested stream banks, the sediment delivery rates given in

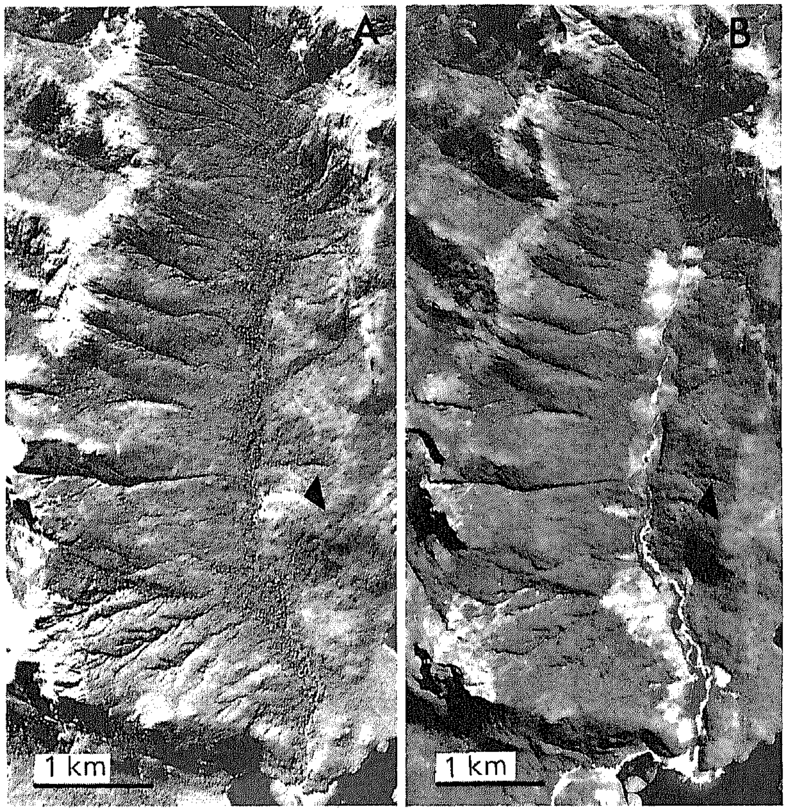

FIG. 3. Mountain Creek: comparative air photos. (A) 1954 (NAPL photo A14331-66): major landslides noted. (B) 1974 (British Columbia photo BC5630-025): old landslide scar noted. Major channel widening is evident between Figs. A and B. Note: scales are accurate only in the valley bottom.

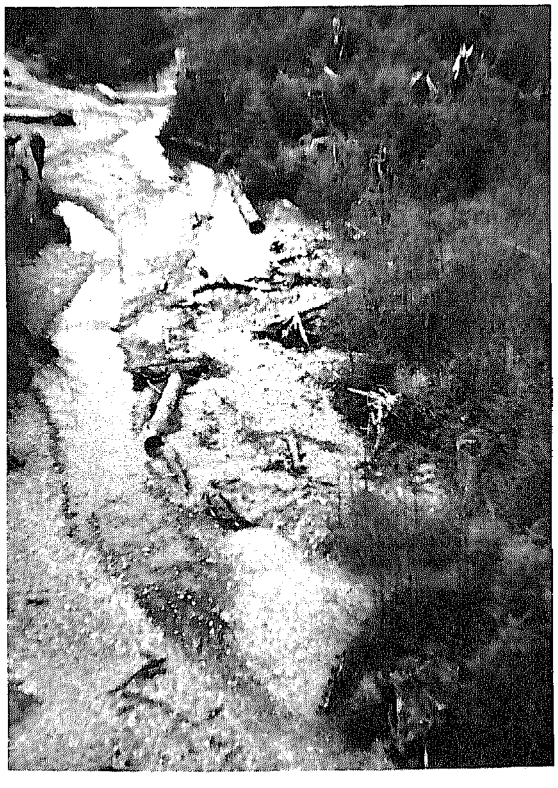

FIG. 4. The extant sediment wedge in Lagins creek tributary (view upstream) at low flow. Note the broadly regular surface, dewatering in parts of the channel, and encroachment of alder onto the edge of the channel zone (taken in October 1981).

Table 2 were used to estimate the volume of riparian land eroded under forested conditions.

The balance of the input contributions in Eq. 1 were estimated by adopting the regionally representative values summarized in Table 2. The rates of soil creep and road surface erosion shown in Table 2 were measured in basins that have steeper slopes and greater road densities and are clear-cut to a greater extent than the study watersheds. Thus, the sediment transfer per unit length of channel by these processes probably would be lower in the study basins, especially along stream reaches that are bordered by a floodplain. Hence, the ranges of sediment production rates shown in Table 2 were applied only to the length of stream channel flanked by steep, soil-covered hillslopes and intersected by landslide scars and roads. This length was determined from 1 : 50 000 scale topographic maps and the 1976 air photos.

The surface of the logging roads was measured directly from air photos to within ±1.0 m. The average road width was measured from photos flown during or shortly after logging, when the road right-of-way was most visible, and the total road length was measured from photos flown after the end of logging, when the road density was greatest. These values were used in conjunction with the rates given in Table 2 to estimate the volume of sediment delivered to the stream channel from the road surfaces.

It was assumed that surface erosion processes are active on landslide scars for 20 years (following Smith et al. 1983) and that the combined processes of soil creep and tree throw result in the movement of the soil column by 2 to 5 mm/year (the sum of reported sediment production rates for these two minor processes on forested slopes) to a depth of 1 m (the mean depth to bedrock

TABLE 1. Physiography and logging history of the study watersheds

Characteristic	Armentieres	Mosquito tributary	Lagins tributary	Mountain
Physiography, geology				
Drainage area[a] (km^2)	3.93	5.38	5.92	12.64
Drainage length[b] (km)	2.75	5.05	5.60	7.30
Drainage relief[c] (m)	490	860	770	910
Average gradient[d]	0.18	0.17	0.14	0.12
Drainage density[e] (km/km^2)	4.2	6.1	5.9	6.7
Highest stream order[e]	4	4	4	5
Major rock type	Basalt flows, pillow lavas, pillow breccia and tuff, minor limestone, volcanic sandstone, and shale		Dark grey calcareous siltstone, greywacke conglomerate, and minor volcanic rocks	Quartz monzonite granite, granodiorite, and quartz diorite
Logging history				
Dates logged	1962–1965 1967–1969	1963–1969	1970–1977	1958 1965–1967
Area logged[e,f] (km^2)	0.29 (7.4) 0.46 (11.7)	1.08 (20.1)	0.63 (10.6)	0.06 (0.5) 1.18 (9.3)
Total	0.75 (19.1)			1.24 (9.8)
Maximum road length (km)	1.20	5.01	5.50	6.73
Road density (km/km^2)	0.31	0.93	0.93	0.53
Road width (m)	5.0	9.4	11.2	7.5
Logging activities[g]				
Logging method	Hand (to 1965), skidded	High lead	Skidded (to 1974), high lead	Skidded (to 1958), high lead
Logging to stream bank	Extensive	Extensive	Extensive	Extensive
Cross-stream felling	Extensive	Limited	Limited	Extensive
Cross-stream yarding	Extensive	Extensive	Extensive	Extensive
In-stream skidding	Extensive	None	Limited	Limited
Stream avulsion along road	Extensive	Limited	Extensive	Limited
Road bridge collapse	None	Major	Minor	None

[a] Area enclosed by the watershed boundary, from 1 : 50 000 scale maps.
[b] Length of the main channel from its outlet to the basin divide, from maps.
[c] Height difference between the main channel at its outlet and the highest point at the basin divide, from maps.
[d] Ratio of drainage relief to drainage length.
[e] From 1 : 10 000 air photography. Highest stream order after Strahler (1952).
[f] Values in parentheses represent the area logged as a percentage of the basin.
[g] From field observations and interviews with logging contractors and supervisors.

or to a strongly indurated layer on disturbed hillslopes in the Queen Charlotte Islands (Smith et al. 1984, Table 1)).

Only the watershed areas adjacent to and upstream of the major fluvial sediment wedges are considered as sediment sources for the input term in Eq. 1. The volume of sediment estimated to be delivered into the drainage network of each sediment wedge by various processes is summarized for the prelogging period (from 1934) and the postlogging period (up to 1982) in Tables 3A and 3B, respectively; the total volume of sediment produced by each process is also indicated. A range of production and delivery volumes is presented for each sediment source; landslide and postlogging stream bank ranges incorporate the error associated with measurement imprecision, while the other estimates reflect the range of representative process rates shown in Table 2. For each wedge (three in Armentieres Creek and one each in the other three creeks), the total volumes of sediment production and delivery are presented as an extreme range (the sum of all positive and negative extremes) and as the most probable range; the latter is the square root of the sum of squared errors, in which a nonstatistical error (quoted as an outside limit, such as a measurement uncertainty) is assumed to be equivalent to a two standard deviation statistical error.

Prior to logging, the most important sediment delivery processes are stream bank erosion, landslides, and soil creep and tree throw. Each process contributes up to 40%, together accounting for almost 90%, of the total sediment input. This balance changes after logging to one dominated by stream bank and landslide inputs; these sediment sources together contribute 75–90%, individually accounting for up to 85%, of the total. Soil creep, tree throw, and road surface erosion constitute the apparently most important minor processes.

The relatively greater role of stream bank and landslide inputs since logging is accompanied by up to an order of magnitude increase in the total volume of sediment delivered to the stream channels. This increase is accounted for primarily by massive bank erosion in Mosquito tributary, Lagins tributary, and Mountain creeks and by high landslide inputs to Armentieres Creek.

Riparian erosion and channel enlargement were initiated in the study watersheds, except in Lagins tributary creek, during the early to middle 1960's. By 1976, channel width had increased by 65 and 100% along the sediment wedge reaches in Mosquito tributary creek and Mountain Creek (Fig. 3), respectively, and by 50% along the upper wedge reach of Armentieres Creek. In Lagins tributary creek (Fig. 4), the stretch of haul road along which the stream was diverted and the sediment wedge developed increased in width by 190% between 1970 and 1976. A reduction in active sediment wedge width

TABLE 2. Representative rates of sediment production on slopes and delivery to streams in the Pacific Northwest

Process	Watershed condition	Rate of sediment production	Rate of sediment delivery to stream (m^3/km channel per year)	Sources
Soil creep	Forested slopes	1–3 mm/year	0.9–4	Dietrich and Dunne 1978 Lehre 1982 Swanson, Fredriksen et al. 1982 Madej 1982
	Logged slopes	2–5 mm/year	6–40	Barr and Swanston 1970 Swanston 1981
Tree throw	Forested slopes	1–2 mm/year	0.1–1	Madej 1982 Reid 1981 Swanson, Fredriksen et al. 1982 Dietrich et al. 1982
Landslides[a]	Forested	9–72 m^3/km^2 basin per year	3–10	O'Loughlin 1972 Fiksdal 1974 Morrison 1975 Swanson and Dyrness 1975 Reid 1981 Swanson et al. 1981 Lehre 1982 Madej 1982 Swanson, Fredriksen et al. 1982
	Logged and roaded	22–3 500 m^3/km^2 basin per year	9–20[b]	O'Loughlin 1972 Swanson and Dyrness (1975) Reid 1981 Swanson et al. 1981 Madej 1982
Surface erosion	Forested slopes	4–10 m^3/km^2 basin per year	0.4–0.9	Lehre 1982 Swanson, Fredriksen et al. 1982 Megahan and Kidd 1972*b*
	Slide scars	1000–4000 m^3/km^2 scar per year	0.9–5	Reid 1981 Lehre 1982
	Logged slopes	16 m^3/km^2 basin per year	—[c]	Megahan and Kidd 1972*b*
	Roads during use	10 000 – 15 000 m^3/km^2 road per year		Reid 1981 Reid and Dunne 1984 Lehre 1982
	Roads, 1st year of disuse	1000–2000 m^3/km^2 road per year	5–30	Megahan and Kidd 1972*a* Hornbeck and Reinhart 1964
	Abandoned roads	100–500 m^3/km^2 road per year		
Stream banks[d]	Forested	2–11 m^3/km channel per year	2–11	Reid 1981 Lehre 1982
	Logged	160–420 m^3/km channel per year	160–420	Toews and Moore 1982

[a] This term includes debris slides, avalanches, flows, and torrents.

[b] Derived from Reid (1981) and Madej (1982). Higher rates of sediment production reported in other studies cannot be expressed in cubic metres per kilometre of channel per year because drainage densities are not cited.

[c] Rate cannot be expressed in cubic metres per kilometre of channel per year because drainage density is not cited.

[d] Higher delivery rates under forested conditions (up to 160 m^3/km channel per year) are reported by Toews and Moore (1982). As with their postlogging rates, this reflects averaging over short study reaches rather than along the entire drainage network.

TABLE 3. Volumes of sediment delivered to the streams from various sources[a]

(A) Prior to logging[b]

Sediment source[c]	Armentieres Creek								Mosquito tributary creek		Lagins tributary creek		Mountain Creek	
	Upper wedge		Middle wedge		Lower wedge		Total							
	m³ (×10³)	%	m³ (×10³)	%	m³ (×10³)	%	m³ (×10³)	%	m³ (×10³)	%	m³ (×10³)	%	m³ (×10³)	%
Stream banks	0.5–2.6	20–38	0.2–1.2	20–41	0.1–0.8	14–36	0.8–4.6	19–39	1.2–6.3	21–39	1.6–8.9	19–36	3.8–20.9	18–36
Landslides	0.9–1.4	36–20	0.2–0.3	20–10	0.1–0.1	14–5	1.2–1.8	29–15	1.4–2.2	25–14	2.8–4.5	33–18	7.1–11.3	34–19
	(2.9–4.6)		(0.7–1.1)		(0.3–0.5)		(3.9–6.2)		(3.5–5.7)		(3.7–6.0)		(7.6–12.1)	
Slide scars	0.1–0.2	4–3	0.0–0.1	0–4	0.0–0.1	0–4	0.1–0.3	2–3	0.1–0.3	2	0.2–0.9	2–4	0.9–3.6	4–6
	(0.2–0.7)		(0.0–0.1)		(0.0–0.1)		(0.2–0.9)		(0.2–0.9)		(0.3–1.2)		(1.0–3.9)	
Soil creep and tree throw	0.9–2.3	36–33	0.5–1.1	50–38	0.3–0.7	43–32	1.7–4.1	40–34	2.3–5.7	41–35	3.2–8.1	37–33	7.6–19.0	37–32
Slope wash	0.1–0.4	4–6	0.1–0.2	10–7	0.2–0.5	29–23	0.4–1.1	10–9	0.6–1.6	11–10	0.8–2.1	9	1.5–3.8	7
Total														
Extreme range	2.5–6.9		1.0–2.9		0.7–2.2		4.2–11.9		5.6–16.1		8.6–24.5		20.9–58.6	
	(4.6–10.6)		(1.5–3.7)		(0.9–2.6)		(7.0–16.9)		(7.8–20.2)		(9.6–26.3)		(21.5–59.7)	
Most probable range	3.4–6.0		1.4–2.5		1.0–1.9		5.8–10.3		7.7–14.0		12.0–21.1		29.1–50.4	
	(6.1–9.1)		(2.0–3.2)		(1.3–2.2)		(9.4–14.5)		(10.7–17.3)		(13.3–22.6)		(29.9–51.3)	
Contributing area (km²)	1.4		2.1[d]		3.8[d]		3.8		5.4		5.8		12.1	

(B) Since logging[b]

Sediment source[c]	Armentieres Creek								Mosquito tributary creek		Lagins tributary creek		Mountain creek	
	Upper wedge		Middle wedge		Lower wedge		Total							
	m³ (×10³)	%	m³ (×10³)	%	m³ (×10³)	%	m³ (×10³)	%	m³ (×10³)	%	m³ (×10³)	%	m³ (×10³)	%
Stream banks	3.7–7.7	18–20	0.2–0.9	5–11	0.1–0.6	4–13	4.0–9.2	14–18	15.1–31.8	53–56	28.8–60.2	85	23.6–49.2	69–68
Landslides	15.4–24.6	73–65	3.7–5.9	82–68	1.6–2.6	70–54	20.7–33.1	75–64	6.5–10.4	23–19	0.3–0.4	1	3.6–5.8	10–8
	(23.4–37.4)		(5.6–9.0)		(2.5–4.0)		(31.5–50.4)		(7.8–12.4)		(0.3–0.5)		(33.5–53.5)	
Slide scars	0.9–3.6	4–9	0.2–0.8	4–9	0.1–0.4	4–8	1.2–4.8	4–9	0.4–1.6	1–3	0.0–0.1	0–1	0.5–1.9	1–3
	(1.4–5.5)		(0.3–1.2)		(0.1–0.6)		(1.8–7.3)		(0.5–1.9)		(0.0–0.1)		(4.3–17.2)	
Soil creep and tree throw	0.7–1.7	3–4	0.3–0.8	7–9	0.2–0.6	9–13	1.2–3.1	4–6	1.6–4.0	6–7	1.2–2.9	3–4	4.4–11.0	13–15
Slope wash	0.2–0.3	1	0.1–0.2	2	0.2–0.4	9–8	0.5–0.9	2	0.7–1.2	2	0.4–0.8	1	1.1–2.3	3
Road surfaces	0.1–0.1	1	0.0–0.1	0–1	0.1–0.2	4	0.2–0.5	1	3.1–5.8	11–10	3.3–6.1	10–8	1.2–2.6	4–3
Road bridge	—	—	—	—	—	—	—	—	1.3–1.6	4–3	Minor		Not applicable	
Total														
Extreme range	21.0–38.0		4.5–8.7		2.3–4.8		27.8–51.6		28.7–56.4		34.0–70.5		34.4–72.8	
	(29.5–52.7)		(6.5–12.2)		(3.2–6.4)		(39.2–71.4)		(30.1–58.7)		(34.0–70.6)		(68.1–135.8)	
Most probable range	24.3–34.7		5.4–7.8		2.9–4.2		32.7–46.7		33.8–51.3		36.5–68.0		40.3–66.9	
	(33.5–48.7)		(7.5–11.2)		(3.9–5.7)		(45.1–65.5)		(35.5–53.3)		(36.5–68.1)		(84.1–119.8)	

[a] Volumes of total sediment production are in parentheses, but are not shown if a ratio of unity exists between sediment production and delivery.

[b] Periods of record are given in Table 4.

[c] Measured values are shown in boldface; value derived from regional representative rates (Table 2) are shown in lightface.

TABLE 4. Rates of landslide erosion and sediment transfer to creek before and after logging[a]

Watershed	Watershed condition	Period of record (years)	Total sediment production (m^3/km^2 per year)			Sediment input to creek (m^3/km^2 per year)			Sediment delivery ratio[b] (m^3/km^2 per year)		
			Unlogged	Logged	Ratio	Unlogged	Logged	Ratio	TSP	SIC	Ratio
Armentieres Creek	Prelogging	30	42	—	—	13	—	—	42	13	0.3
	Postlogging	19	607	393	0.6	452	21	0.05	566	370	0.7
Mosquito tributary	Prelogging	30	29	—	—	11	—	—	29	11	0.4
	Postlogging	19	95	112	1.2	87	63	0.7	98	82	0.8
Mountain Creek	Prelogging	32	26	—	—	24	—	—	26	24	0.9
	Postlogging	17	178	518	2.9	25	5	0.2	211	23	0.1
Lagins tributary	Prelogging	36	23	—	—	18	—	—	23	18	0.8
	Postlogging	13	6	0	0	5	0	0	5	4	0.8

[a] Volumes refer to the entire watershed, hence are not simply comparable with the results in line 2 of Table 3. Contributing areas are given in Table 1.

[b] TSP, total sediment production from entire (logged and unlogged) watershed; SIC, sediment input to creek from entire (logged and unlogged) watershed.

occurred between 1976 and 1982 in all four watersheds as a result of the rapid recolonization of the wedge surface by streamside vegetation (primarily red alder; Fig. 4).

The estimated rates of landslide erosion before and after logging and in the forested and logged parts of the entire study watersheds are summarized in Table 4 and discussed in detail by Roberts (1984). Table 4 refers to the period from 1934 to 1982. Three points deserve comment: the variation in sediment production rates in forested terrain between the prelogging and postlogging periods, the effect of logging on sediment production rates, and the ratio between sediment production and delivery rates.

In the forested parts of the study watersheds, the rate of sediment production is different between the prelogging and postlogging periods. This is attributable mainly to the inherently episodic nature of landslides, which is a problem when attempting to isolate the impact of harvesting activities. However, K. M. Rood (personal communication) also reports, from a broader regional survey, an increased frequency of failures since about 1960. In the Mountain Creek (Fig. 3) and Mosquito tributary creek basins, clear-cuttings produced more sediment than forested areas; this concurs with results reported for the Pacific Northwest in general (see O'Loughlin 1972; Swanson and Dyrness 1975; Swanson et al. 1981). In Armentieres Creek, the reverse situation occurs because the average slide volume is four times larger in the forested area (Rood (1984) observed that failures in forested terrain are, in general, about twice as large as in clearings). Lagins tributary creek experienced no failures in the low-gradient clear-cuttings. In general, the study watersheds experienced a far smaller change after logging than is common in the Queen Charlottes (Rood (1984) reports a 30 times increase in landslide volume following logging) because only the lower slopes and valleys were cleared. Regionally, debris torrents are very important in the postlogging increase of mass wasting, whereas in the study basins, 97% of the failures were classified as debris slides. On average, 60% of the sediment estimated to be mobilized by landslides reached the drainage networks of the study watersheds.

A special case of sediment delivery occurred in Mosquito tributary creek: the collapse of a haul road bridge released approximately 1450 ± 150 m^3 of predominantly coarse-grained material directly into the channel, causing local aggradation and stream flow diversion along the road. A similar collapse in Lagins tributary effected a stream diversion, but did not itself contribute a notable volume of sediment.

Overall, the variation of the results is the consequence of the variety of physiographic settings and activities associated with logging and emphasizes the importance of specific histories of land management.

Sediment storage in channels

The volume of material stored in the stream channel in the major fluvial sediment wedges (cf. Fig. 4) forms the transient storage component (ΔS) of the sediment budget as formulated in Eq. 1.

The surface geometry of each sediment wedge was determined by standard surveying techniques. The upstream limit of a sediment wedge was easily identified because the adjoining upper reaches usually were scoured to bedrock, while the downstream terminus was distinguished by the sudden change in channel width and gradient (see Fig. 5). The surface gradients were less than 3.5°.

Although the long profile of the surface of the sediment wedge can be surveyed, there is no technique that can directly delineate the profile of the base of the sediment wedge (i.e., the preaggradation long profile). Upon the widespread observation that stream profiles over considerable distances usually are concave (e.g., Mackin 1948; Miller 1958), the base is assumed to be a smooth concave curve between bedrock control points. The mathematical curve that best fits the surveyed points above and below a sediment wedge and the bedrock outcrops along it was found by attempting logarithmic and quadratic polynomial function fits.

The volume of a sediment wedge was estimated by measuring its length and depth from the long profile plots (Fig. 5) and obtaining widths from the 1976 air photos. Each wedge was divided into 50-m subunits and the mean values of width and depth for each subunit were used to compute a total volume as

$$[2] \quad S_t = 50 \sum_{i=1}^{n} \bar{W}_i \bar{D}_i$$

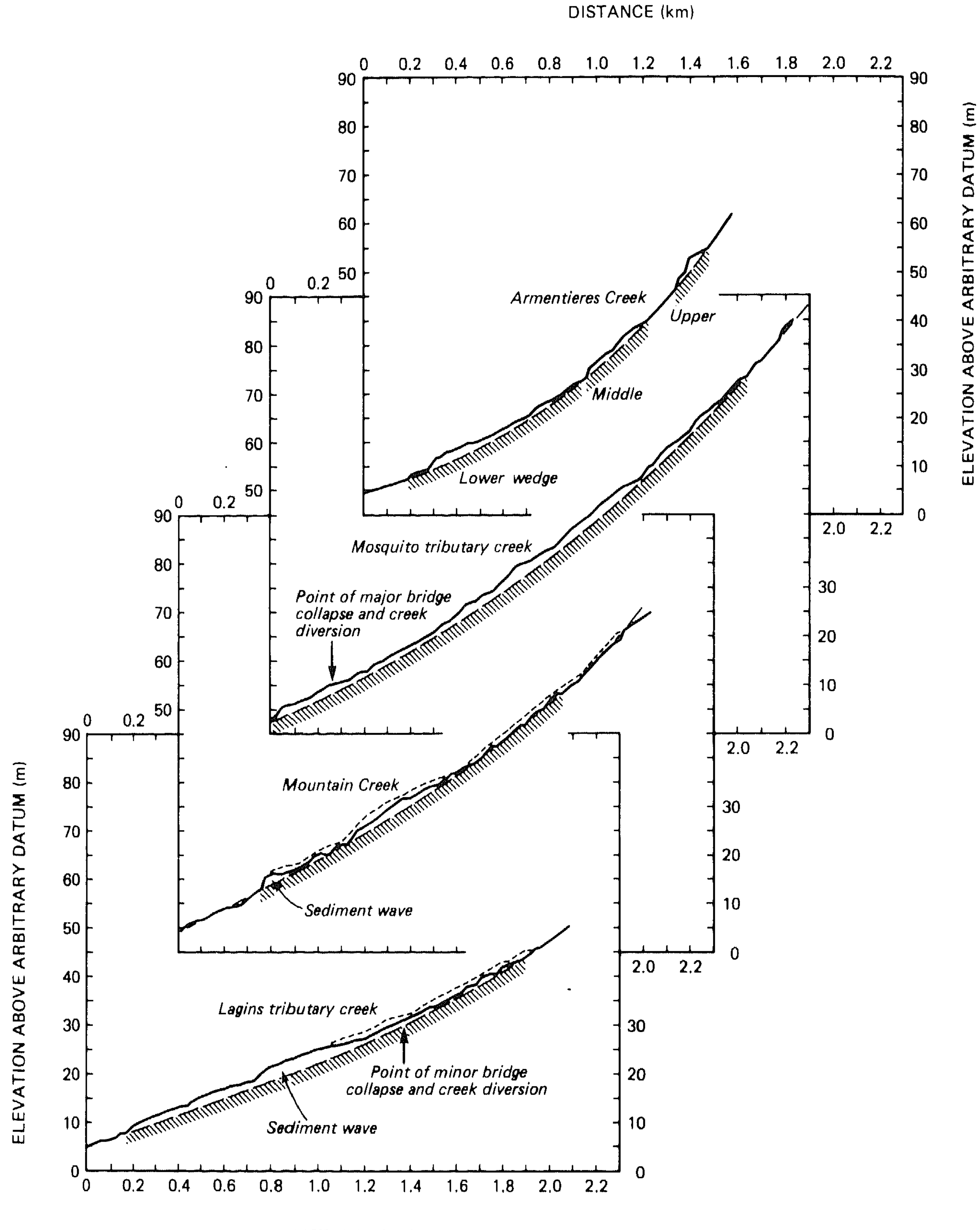

FIG. 5. Long profiles of sediment wedges in the study creeks. The solid line is the extant long profile along the regular aggradational surface; the dashed line (— —) represents a mathematically fitted smooth long profile to approximate the channel bed under the wedge; hatching (▨) represents the longitudinal extent of wedge sediments; pecked line (- - - -) represents the terrace surface.

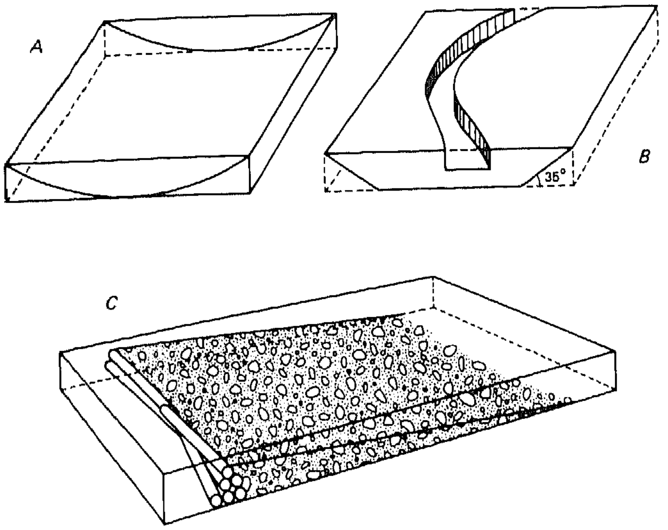

FIG. 6. Geometry of a sediment wedge and normal in-channel sediment storage. (A) Rectangular and circular arc sections (columns A and B, Table 5) based upon survey of the wedge surface and cross-section assumptions. (B) Trapezoidal section based on the subtraction of a triangular volume at each bank to represent a repose angle slope for noncohesive, granular material (columns A–C, Table 5), and stream channel volume removed (column D, Table 5). (C) Debris accumulation behind a log step: representative volumes are drawn from observations by Hogan (1985) (see text) (column E, Table 5).

where S_t is the total volume of the sediment wedge (cubic metres), i is the subunit number, n is the maximum number of subunits, $\bar{W}_i$ is the mean width of subunit (metres), and $\bar{D}_i$ is the mean depth of subunit (metres).

This procedure calculates the volume of a rectangle, although most stream channels are more semicircular in cross section. Thus, rectangular sediment wedge volumes are maximum estimates, to which adjustments are made depending on channel shape, stream incision, and antecedent storage factors (see Fig. 6). The volume occupied by the incised stream channel was estimated from field surveys and deducted from the wedge volume. The volume of material stored behind log steps or in-stream obstructions prior to the development of a sediment wedge should be subtracted from the contemporary wedge volume. From measurements in streams within the study area, Hogan (1985) found the mean volume of sediment stored behind in-stream obstructions in forested watersheds to be 0.03 to 0.06 m^3 per square metre of channel area. This value was applied to the area of each sediment wedge to estimate a volumetric reduction for antecedent storage. Further reduction of sediment wedge volumes is possible if bedrock intrudes into the smoothly concave base profiles. Apart from the adjustments made already for bedrock outcrops, there is no basis for an objective evaluation of bedrock microtopography. This factor has, therefore, been ignored. Table 5 indicates two volume range estimates of each wedge; the actual volumes probably lie within the total range.

Sediment output

The transport of material through the fluvial sediment wedge reaches represents the output term in the sediment budget, ϕ in Eq. 1. There have been no direct field measurements of sediment discharge. Sediment output during the prelogging period is equated with input, on the assumption that $\Delta S \approx 0$. This

TABLE 5. The estimated volume of sediment stored in the sediment wedges[a]

Watershed	Sediment wedge Length (m)	Mean width (m)	Mean depth (m)	Rectangular wedge volume (m^3, $\times 10^3$) (A)[b]	Semicircular wedge volume (m^3, $\times 10^3$) (B)[b]	Triangular subtraction volume (m^3, $\times 10^3$) (C)[b]	Stream channel volume (m^3, $\times 10^3$) (D)[b]	Antecedent storage volume (m^3, $\times 10^3$) (E)[b]	Sediment wedge volume estimates B–D–E (m^3, $\times 10^3$)	A–C–D–E (m^3, $\times 10^3$)
Armentieres Creek										
Upper wedge	160	35	1.6	9.0	6.2	0.6	0.6	0.2–0.3	5.3–5.4	7.5–7.6
Middle wedge	300	27	1.2	9.4	6.9	0.6	0.5	0.2–0.4	6.0–6.2	7.9–8.1
Lower wedge	770	22	1.5	25.3	16.8	2.5	1.4	0.7–1.5	13.9–14.7	19.9–20.7
Total				43.7	29.8	3.7	2.5	1.1–2.2	25.1–26.2	35.3–36.4
Mosquito tributary	2050	28	1.7	99.9	57.0	8.5	8.6	1.2–2.5	45.9–47.2	80.3–81.6
Lagins tributary	1650	16	1.5	40.0	28.1	5.3	7.5	1.7–3.4	17.2–18.9	23.9–25.5
Mountain Creek	1300	36	0.8	39.5	29.0	1.2	3.9	0.8–1.6	23.5–24.3	32.8–33.6

[a] Based on 1983 long profile surveys and widths derived from 1976 air photographs, which reveal the greatest development.
[b] See Fig. 6.

TABLE 6. Volumes and rates of sediment input, transport, and storage in the streams[a]

(A) Prior to logging

Watershed	Sediment input volume (m^3, $\times 10^3$)	Sediment stored in wedge reach[b] (m^3, $\times 10^3$)	Sediment transport[c] m^3/year	Sediment transport[c] t/year[e]	Sediment "residence" time[d] (years)
Armentieres Creek					
Upper wedge	3.4–6.0	0.2–0.3	110–200	200–360	1–3
	(2.4–4.7)		(80–160)	(140–280)	(1–4)
Middle wedge	1.4–2.5	0.2–0.4	160–280[f]	290–510[f]	1–4[f]
	(1.0–2.0)		(110–230)[f]	(200–400)[f]	(2–6)[f]
Lower wedge	1.0–1.9	0.7–1.5	190–340[f]	350–620[f]	3–12[f]
	(0.5–1.3)		(130–270)[f]	(230–480)[f]	(4–15)[f]
Total	5.8–10.3	1.1–2.2	190–340	350–620	3–12
	(3.9–8.0)		(130–270)	(230–480)	(4–15)
Mosquito tributary	7.7–14.0	1.2–2.5	260–470	460–840	3–10
	(5.3–10.8)		(180–360)	(320–650)	(3–13)
Lagins tributary	12.0–21.1	1.7–3.4	330–590	600–1060	3–10
	(8.0–16.0)		(220–440)	(400–800)	(3–14)
Mountain Creek	29.1–50.4	0.8–1.6	910–1580	1640–2840	0.5–2
	(19.3–37.9)		(600–1180)	(1090–2130)	(0.5–2)

(B) After logging

Watershed	Sediment input volume ($\times 10^3$)	Sediment stored in wedge[g] ($\times 10^3$)	Sediment transport[c] m^3 ($\times 10^3$)	Sediment transport[c] m^3/year	Sediment transport[c] t/year	Sediment "residence" time[d] (years)
Armentieres Creek						
Upper wedge	24.3–34.7	5.3–7.6	16.7–29.4	900–1500	1600–2800	4–8
	(14.9–21.5)	(4.8–6.8)	(8.1–16.7)	(400–900)	(750–1600)	(5–17)
Middle wedge	5.4–7.8	6.0–8.1	14.0–31.2[f]	700–1600[f]	1300–2950[f]	4–12[f]
	(3.1–4.6)	(5.4–7.3)	(7.3–16.7)[f]	(400–900)[f]	(700–1600)[f]	(6–18)[f]
Lower wedge	2.9–4.2	13.9–20.7	0.0–21.5[f]	0–1100[f]	0–2000[f]	>13[f]
	(1.5–2.4)	(12.5–18.6)	(0.0–6.6)[f]	(0–350)[f]	(0–650)[f]	(>19)[f]
Total	32.7–46.7	25.1–36.4	0.0–21.6	0–1100	<2050	>23
	(19.5–28.5)	(22.6–32.8)	(0.0–5.9)	(0–300)	(<550)	(>75)
Mosquito tributary	33.8–51.3	45.9–81.6	0.0–5.4	0–300	<500	>150
	(22.3–37.7)	(41.3–73.4)	(0.0)	(0)	(0)	(>>150)
Lagins tributary	36.5–68.0	17.2–25.5	11.0–50.8	800–3900	1450–7000	4–32
	(28.0–56.3)	(15.5–23.0)	(5.0–40.8)	(400–3100)	(700–5650)	(5–58)
Mountain Creek	40.3–66.9	23.5–33.6	6.7–43.4	400–2600	700–4600	9–84
	(30.6–54.4)	(21.2–30.2)	(0.4–33.2)	(20–2000)	(50–3500)	(11–1500)

[a] Values in parentheses refer to bed load calibre material only.
[b] Antecedent storage volume (column E) of Table 5 (see text for discussion).
[c] For period of record, see Table 4. In Table 6A, transport = input; in Table 6B, transport = input − sediment stored in wedge.
[d] Sediment stored in channel divided by sediment transport per year.
[e] Based on 1.8 t/m^3.
[f] Includes the volume of sediment exported from upstream reaches.
[g] From Table 5.

assumption is justified by our failure to find extraordinary fluvial sediment accumulations in any unlogged Queen Charlotte Island streams (although transient accumulations of unmodified landslide debris do occur). In the postlogging period output is quantified from the difference between estimated input and fluvial storage volumes. Because of the errors inherent in this method, morphologic evidence was sought that would provide an independent check on its accuracy.

The volumes and rates of fluvial sediment transport in the study watersheds are given in Tables 6A and 6B based upon these indirect methods. The mode of transport depends largely on particle size, with material finer than 1–2 mm representing suspended load and the coarser fraction becoming bed load. As approximately 90% of the wedge subsurface material is coarser than 2 mm (determined from sediment texture analyses), the mobility of a sediment wedge is determined primarily by bed load transport. The estimated ranges of bed load transport in the study creeks are shown in parentheses in Tables 6A and 6B; sediment input ranges were estimated on the basis that about 60% of landslide material (R. B. Smith, personal communication) and 90% of riparian and soil creep material (measured) is of bed load calibre (i.e., coarser than 2 mm), while the other transfer processes mobilize mostly finer sediments.

Volumes of 200–600 m^3/year were estimated to be fluvially transported along Mosquito tributary, Lagins tributary, and Armentieres creeks prior to logging. The rate of 900–1600 m^3/year estimated for Mountain Creek probably is too high; the particularly high density of low-order channels in this basin inflates the estimated volume of sediment delivered from streamside sources, resulting in a large difference between sediment input and storage volumes. If the study creeks in their unlogged state were approximately in equilibrium, with 0.03–0.06 m^3 sediment stored per square metre of channel area (after Hogan 1985), then in-stream sediment along the subsequent wedge reach, on average, was "resident" for less than 10 years (see Table 6A). There was no evidence detectable on air photographs for major in-stream sediment storage prior to logging (cf. Fig. 3).

Since logging, the mean annual rate of sediment transport has increased in Mountain Creek (to 2600 m^3/year) and Lagins tributary (to 3900 m^3/year), but decreased slightly in Mosquito tributary (by 0–300 m^3/year). The high rate in Lagins tributary is a consequence of the comparatively recent development of its sediment wedge. The much lower rate in Mosquito tributary is corroborated by comparing the volume of material supplied by the collapsed road bridge (1300–1600 m^3) with the volume of sediment stored in the downstream wedge reach (2600–4200 m^3; see Fig. 4). The bridge collapsed circa 1970 and there were no adjacent sediment sources. The condition of the channel beyond the end of the wedge indicates that no bed material passes beyond the wedge, so we infer that the difference between the total wedge volume and that derived from the bridge embankment was fluvially transported from upstream at a mean rate of 100–200 m^3/year.

The postlogging rates of sediment transport in Armentieres Creek are estimated from the volumes of material transferred between the three sediment wedges (see Table 6B). Between 1962 and 1982, the upper wedge reach apparently received more sediment from adjacent and upstream sources than is currently stored there. The surplus was transported through the middle wedge, which appears to be in balance with its direct source area, and deposited in the lower wedge reach (which began to aggrade in 1965); the rate of interwedge transfer ranged from 700 to 1600 m^3/year. Some sediment was transported further downstream, which represents a net sediment export rate of 0 to 1100 m^3/year.

It is noteworthy that despite the generally greater postlogging rates of sediment transport, the "residence" time of the bed sediment in the creeks has increased, in some cases by much more than an order of magnitude.

As a check on these sediment transport estimates, the pattern of estuarine sedimentation at the mouths of Armentieres, Lagins, and Mountain creeks during the past 50 years was examined from air photos and hydrographic charts, but revealed no evidence of progradation. The most favourable conditions for estuarine progradation exist at Armentieres Creek, because the terminus of its lower wedge is only 180 m from the estuary. However, the volume of sediment exported from the lower wedge (see Table 6B) would result in an average estuarine progradation of less than 6 mm/year.

The presence of discontinuous and unpaired stream terraces along the upstream portions of sediment wedges in Mountain Creek and Lagins tributary (see Fig. 5) provides another basis for the quantification of sediment transport. The heights of these terraces were measured during field surveys and linear interpolation between points enabled the terrace "profiles" to be superimposed onto the long profile plots. The volumetric difference between present wedge profiles and terrace profiles was estimated with the same procedure as that used for sediment storage calculations (see Eq. 2).

Observations from air photos suggest that the terraces were produced by the episodic, downstream movement of sediment derived in large measure from erosion of the upstream portion of the initial sediment wedge and are not the remnants of a single stream-length episode of incision. Much of the coarse sediment present in the downstream portion of a wedge originates from this stream incision into the upstream wedge deposits in the years after their initial deposition. The remaining material in the downstream wedge reach often is supplied by the lateral erosion of adjacent stream banks, induced by channel aggradation and stream braiding that accompanies the arrival of the sediment "wave" from upstream. The effect of this additional sediment recruitment is to offset the downstream attenuation of sediment transfer.

In Mountain Creek (Fig. 3), the sediment "wave" is approximately 100 m long and, by 1976, had progressed two-thirds of the distance along the 1300-m sediment wedge zone. Between 1976 and 1982, the "wave" travelled a further 400 m downstream at a mean sediment transport rate of 1600 m^3/year. At present, Mountain Creek has relatively stable upstream reaches, with a revegetated wedge surface and an entrenched stream channel, and unstable lower reaches where aggradation, braiding, and lateral bank erosion are occurring. However, the major rain storm in January 1984 was the first event in at least 20 months to have produced any apparent morphological change in the lower reach. The resultant bank erosion, displacement of in-stream large organic debris, and channel aggradation by fine gravels (L. Beaven, personal communication) suggests disturbance and transport of the downstream deposits, probably into the estuary.

Lagins tributary developed a sediment wedge along a 1650-m section of haul road as a result of creek diversion during a 1976 winter storm. By 1982, the creek had become incised into the wedge deposits along the upper two-thirds of its length, while the lower one-third contained the sediment "wave." Approximately 15 800 m^3 of sediment was stored in the latter, of which one-third was estimated to be derived from erosion of contiguous stream banks and two-thirds presumably represents sediment input from upstream since 1976; this corresponds to a mean sediment transport rate of 1700 to 1800 m^3/year. At present, the sediment wedge is relatively immobile as a result of revegetation and "armouring" of its surface by the larger cobbles.

Morphological evidence of the low rate of sediment transport within Mosquito tributary creek is provided by the absence of terraces and the reestablishment of vegetation along the sediment wedge. The presence of a dense tree cover downstream of the wedge terminus and along the section of haul road-cum-contemporary stream channel implies that negligible bed load is exported from the sediment wedge.

Causes of fluvial sediment wedge initiation and development

Since logging, more than half of the total sediment input to Mountain Creek, Mosquito tributary creek, and Lagins tributary creek has been derived by riparian erosion (Table 3B). Without stream bank retreat, there would be significantly less sediment available to initiate a wedge and insufficient lateral room for wedge development. Therefore, the factors leading to sediment wedge inception and growth following logging are closely related to those causing stream bank destabilization.

The possibility that the stream banks were destabilized by a logging-related or longer term natural increase in stream flow was examined. Hydrologic changes accompanying timber harvesting in the Pacific Northwest have been varied and site specific (for review, see Roberts 1984). The present-study watersheds were largely high lead yarded and have low road densities, so that the area of soil compaction is limited and peak flows are unlikely to have been augmented by rapid overland flow. During the past century, periods of above-normal precipitation and stream runoff in the Queen Charlotte Islands (see Karanka 1986) were not coincident with sediment wedge initiation. In other cases of notable stream bank erosion, high flows per se have not been implicated (see Rice 1981; Toews and Moore 1982; Lyons and Beschta 1983).

Stream banks may be destabilized by landslides that deliver sediment to short reaches of channel sufficiently rapidly to initiate substantial aggradation. Channel aggradation may deflect flow against the stream banks, which are then undercut and retreat by collapse; the added sediment may enhance aggradation and so the cycle may be repeated. The largest landslide identified in the Mountain Creek basin delivered approximately 8300 m^3 of sediment into the trunk stream circa 1950, when the basin was forested (see Fig. 3). However, bank retreat and wedge development did not occur until the onset of logging, 15 years later. Sediment from the major landslide, once fluvially entrained, appears to have passed relatively quickly through the channel or, at least, to have been too greatly dispersed to form a noticeable fluvial wedge. In Armentieres Creek watershed, the upper wedge consists partly of material that was delivered by an 8700-m^3 debris flow in 1975. As channel enlargement in the upper reaches was initiated in 1970, the input from the debris flow (which originated in unlogged terrain) furthered, rather than triggered, the development of the sediment wedge. Logging activities on hillslopes are unlikely to have generated the sediment wedges directly, because the rate of sediment delivery to the study creeks has been lower in clear-cut areas than in forested areas (see Table 4), probably because it is mainly lower slopes that have been cleared. In many other Queen Charlotte watersheds, sediment delivery is greater from clear-cuttings (Rood 1984), but fluvial sediment wedges are not observed.

In the study watersheds, the stream banks probably were destabilized by the streamside and in-stream logging practices. Three lines of evidence support this conclusion: (*i*) the absence of severe bank erosion and sediment wedges in forested basins in the Queen Charlotte Islands during the past 300 years, (*ii*) the coincidence of severe bank retreat, wedge development, and streamside logging activity in the study basins, and (*iii*) the occurrence of significant riparian erosion in other basins in the Pacific Northwest that have been subjected to similar timber harvesting practices.

In forested watersheds in the Queen Charlotte Islands, stream bank retreat is confined mainly to local "pockets" of erosion between old-growth trees. As the streamside vegetation in these watersheds is more than 250 years old (according to forest cover maps compiled by the British Columbia Forest Service), episodes of major riparian erosion apparently have not occurred during the past three centuries. Despite the probable occurrence of exceptional hydrologic and seismic events during the 250 years prior to logging, the absence of old alluvial terraces and the prevalence of old-growth conifers beside the study creeks in the 1930's implies that earlier episodes of channel aggradation and bank erosion were limited in magnitude and duration. For example, the major rain storm in January 1984 produced only a local infilling of pools along forested creeks within the study area (D. L. Hogan and L. Beaven, personal communication). We conclude that most of the drainage network in forested basins appears not to have undergone any significant morphologic change during the past 300 years.

Logging activities are implicated as the triggering agent in stream bank destabilization because of their temporal correspondence with riparian retreat and sediment wedge appearance in the study watersheds. The absence of fluvial sediment wedges in other logged basins in the Queen Charlotte Islands suggests that on-site circumstances are of paramount importance. The common feature of the logging practices used in the study watersheds is the considerable level of activity in the riparian zone (see Table 1). From investigations conducted throughout the Pacific Northwest, it is well established that streamside logging activities, especially cross-channel felling and yarding, can greatly damage stream banks (Chamberlin 1982).

High flows are a necessary but not always sufficient condition for continued bank retreat and sediment wedge growth. After the passage of a sediment "wave" through a reach, the remaining wedge deposits are stabilized and further bank erosion is hindered by the adoption of a single-thread channel thalweg and by the sedimentary "armouring" and revegetation of the wedge surface. Consequently, the upstream portion of each sediment wedge decreased in active width between 1976 and 1982, despite a large rain storm in October 1978. Contemporary bank erosion and wedge movement occur only during major hydrologic events along downstream reaches, as seen in Mountain Creek in January 1984.

The fluvial sediment wedges represent poor aquatic habitat. The wide, unvegetated channels present large expanses devoid of cover or habitat variety, sporadically mobile sediment in the active wedge may scour substantially during flood so that incubating fish eggs may be lost, and surface dewatering of the gravels during summer low flow may cause rearing fish to perish. In the study streams, the fluvial wedges developed during the mid-1960's and early 1970's are still extant and their habitat quality is little modified after one or two decades.

Summary

In this paper the sediment budget has been established for four severely disturbed small drainage basins in the Queen Charlotte ranges. It is apparent from these results and those from other studies that the absolute magnitude of sediment transfers in a time interval will depend upon drainage basin factors, such as geology, physiography, and antecedent event history, upon particular land management activities, and upon contingent events, such as severe weather, seismic shocks, and the coincident condition of the forest cover. Conclusions about regional conditions in the Queen Charlotte Islands should not be drawn from this study, since the study basins were not chosen to be representative. Indeed, the lack of severe channel aggradation in forested and other logged watersheds in the Queen Charlotte Islands suggests that conditions in the study creeks are linked to the specific, obsolescent logging practices employed there.

Conditions on the unlogged hillsides ought not to be exceptional. Table 4 gives estimates of the volume of sediment mobilized by landslides and the proportion that reaches the stream channels. The values vary widely; production depends upon geology, physiography, and the circumstances of logging;

delivery depends upon the presence or absence of a valley flat between hillslope and channel and the level of slope activity directly above channels. The table also illustrates the comparison between logged, or "disturbed," and undisturbed terrain. No general pattern emerged for sediment production. A lower rate of sediment delivery prevails in logged areas in the study watersheds because only relatively low-gradient slopes were clear-cut. However, sediment production may become substantially greater in logged terrain, as is shown in other studies on the Queen Charlotte Islands (see Wilford and Schwab 1982; Rood 1984).

Table 3 indicates that prior to logging, debris slides were responsible for up to 35% of the total volume of sediment delivered to stream channels but that only Armentieres Creek showed a postlogging increase (up to 75%); the relative drop in the other study basins is a function of fewer debris slides and (or) accelerated riparian erosion. The variation in landslide frequency between basins and between periods reflects their spatially and temporally episodic occurrence.

Fluvial sediment wedges have developed in the channels of the study basins because past riparian logging practices severely disturbed the stream banks and initiated substantial channel widening. Once initiated, they also trap coarse material delivered from upstream and from adjacent slopes and the large volume of sediment resident in the channel may provoke further bank erosion by redirecting the stream. Once developed, fluvial sediment wedges are persistent. They consist nearly entirely of material moved as bed load. The material moves sporadically in high flows and the deposits may gain additional stability as the result of the propensity for the surface gravels to become "armoured" by an imbricate concentration of the coarser grains. It appears that sand and finer material, frequently moveable in suspension, moves quickly through these steep, flashy streams unless trapped in the interstices of the gravel deposits.

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