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Holocene Sediment Production in Lillooet River Basin, British Colombia: A Sediment Budget Approach

La sédimentation à l'Holocène dans le bassin de la Lillooet River, Colombie-Britannique : étude par le biais du bilan sédimentaire

Sedimentierung im Holozàn im Becken des Lillooet River: Studie mittels der Sedimentbilanz

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Article abstract

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HOLOCENE SEDIMENT PRODUCTION IN LILLOOET RIVER BASIN, BRITISH COLUMBIA: A SEDIMENT BUDGET APPROACH

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ABSTRACT A sediment budget approach is used to investigate the sources, storage, and yield of clastic sediment in Lillooet River watershed, in the southern Coast Mountains. The 3150 km² basin is heavily glacierised, and includes a Quaternary volcanic complex which has been active in the Holocene. The sediment yield has been determined from the rate of advance of the delta at the basin outlet. The floodplain of the main river valley is aggrading as the delta advances, and probably has been through most of the Holocene. Major sediment sources in the basin include glaciers and Neoglacial deposits, debris flows, and landslides in the Quaternary volcanic complex. Soil and bedrock creep, bank erosion of Pleistocene glacial deposits, and sediment from logging and agriculture are probably of minor importance. Estimates of sediment production from these sources explain only about half the observed clastic sediment yield plus the rate of valley aggradation. The unexplained sediment production may be associated with paraglacial sediments exposed by glacial retreat from the nineteenth century Neoglacial maximum; alternatively the frequency of occurrence of intermediate scale debris flows and landslides has been seriously underestimated. Sediment supply is highly episodic over time scales of centuries to thousands of years. Major factors in the temporal pattern of Holocene sediment supply are periods of volcanism, large landslides, the retreat of glaciers from the Neoglacial maximum, and recent river engineering works.

RÉSUMÉ *La sédimentation à l'Holocène dans le bassin de la Lillooet River, Colombie-Britannique: étude par le biais du bilan sédimentaire.* L'établissement du bilan sédimentaire sert ici à étudier les sources, le stockage et l'apport de sédiments détritiques dans le bassin versant de la Lillooet River, dans le sud des montagnes Côtières. Le bassin versant de 3150 km² est partiellement englacé et comprend un complexe volcanique quaternaire qui a été actif à l'Holocène. L'apport de sédiments a été déterminé à partir de la vitesse de progression du delta situé à l'embouchure du bassin. La plaine d'inondation de la vallée principale se remblaye avec la progression du delta, ce qui a probablement aussi été le cas pendant la plus grande partie de l'Holocène. Les plus importantes sources de sédiments comprennent les glaciers et les dépôts néoglaciaires, les coulées boueuses et les glissements de terrain dans le complexe volcanique quaternaire. La reptation, l'érosion des rives formées dans les dépôts glaciaires pléistocènes, ainsi que le déboisement et l'agriculture sont probablement des sources mineures. La quantité de sédiments estimée à partir de ces sources ne compte que pour la moitié des sédiments détritiques observés, sans compter le remblaiement de la vallée. La quantité de sédiments non établie pourrait provenir des sédiments paraglaciaires mis à découvert par le retrait glaciaire survenu après l'optimum néoglaciaire du XIX^{e} s. De même, on a grandement sous-estimé la fréquence des coulées boueuses et des glissements de terrain de moyenne envergure. Réparti sur de longues périodes, allant de centaines à des milliers d'années, l'apport en sédiments est très épisodique. Les principaux facteurs qui influencent le modèle temporel de la sédimentation sont les périodes de volcanisme, les grands glissements de terrain, le recul glaciaire après l'optimum du Néoglaciaire et les récents aménagements entrepris sur la rivière.

ZUSAMMENFASSUNG *Sedimentierung im Holozän im Becken des Lillooet River: Studie mittels der Sedimentbilanz.* Mittels einer Sedimentbilanz werden Ursprung, Lagerung und Anschwemmung der Trümmersedimente in der Wasserscheide des Lillooet River in den südlichen Küstenbergen untersucht. Das 3150 km² grosse Becken ist stark vergletschert und umfasst einen vulkanischen Quaternär-Komplex, der im Holozän aktiv war. Die Sedimentanschwemmung war durch die Vorstossrate des Deltas an der Beckenmündung bestimmt. Das Hochflutbett des Haupttals schüttet sich mit dem Vorrücken des Deltas auf und hat dies wahrscheinlich fast im gesamten Holozän getan. Zu den wichtigsten Sedimentquellen in dem Becken gehören Gletscher und neoglaziale Ablagerungen, Trümmerfluss und Bergstürze in dem vulkanischen Quaternär-Komplex. Gekriech von Erde und anstehendem Gestein, die Erosion der Abflachungen in den glazialen Ablagerungen des Pleistozän und Sediment aufgrund von Abholzung und Landwirtschaft sind wahrscheinlich von geringerer Bedeutung. Schätzungen der Sediment-produktion dieser Herkunft erklären nur die Hälfte der beobachteten Trümmersedimentanschwemmung zuzüglich der Rate der Talaufschüttung. Die nichterklärte Sedimentproduktion könnte mit paraglazialen Sedimenten, freigelegt durch den glazialen Rückzug nach dem neoglazialen Hochstand im 19. Jahrhundert, in Verbindung gebracht werden; indessen hat man die Häufigkeit von Trümmerfluss und Bergstürzen mittleren Ausmasses ernstlich unterschätzt. Der Sedimentnachschub geschieht sehr episodisch in Zeiträumen von Jahrhunderten bis Tausenden von Jahren. Die Hauptfaktoren im Zeitmuster des Sedimentnachschubs im Holozän sind Perioden vulkanischer Aktivität, grosse Bergstürze, der Rückzug der Gletscher nach dem neoglazialen Hochstand und neuere Flussbauarbeiten.

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INTRODUCTION

SEDIMENT AND SOLUTE YIELDS

Gross sediment and solute yield data have often been used as an index of denudational processes in a watershed (*e.g.* Saunders and Young, 1983). Unfortunately, non-denudational sources of solutes (Janda, 1971) and clastic sediment redistribution within the watershed (Slaymaker, 1977) complicate the analysis. A central problem concerns that of the role of storage of sediment between the point of its provenance and the mouth of the basin (Meade, 1982). The general model that has been invoked conventionally states that the greatest denudation occurs in the smallest headwater tributaries. Denudation is gradually reduced with increasing size of basin as slopes decrease, precipitation intensity decreases, and more and more sediment from upstream is deposited in storage sites (Vanoni, 1975). This general model has been challenged by Church and Slaymaker (1989) as being particularly inappropriate in glaciated mountain landscapes because it ignores the storage and subsequent reworking of paraglacial sediment. They proposed an alternative model in which sediment yield increases downstream (Fig. 1).

In western Canada, recorded sediment and solute yields range in value from the equivalent of 1 to 500 $m^3\ km^{-2}\ a^{-1}$ (or Bubnoffs[1]; Slaymaker, 1987). Modal values for Canada east of the Cordillera are 1-50 B, except in those basins that are heavily agriculturally disturbed or where urban land development is occurring; in the Cordillera the full range from 1-500 B is experienced but with modal values from 10-200 B (Slaymaker, 1987). Lillooet River basin has a long term estimated sediment and solute yield of about 417 B but for the post-1948 period over 600 B has been estimated. The most intriguing observation is that the lowest yields in the Cordillera (1-10 B) occur in the unglacierised headwater tributaries. This observation contradicts the conventional model referenced earlier. But it is consistent with the recorded measurements of slope processes which have individually accounted for less than 1 B when extrapolated to drainage basin scale (Caine, 1974; Slaymaker, 1977).

In an attempt to test the Church and Slaymaker (1989) model and to reconcile the problem of high downstream sediment yields and apparently low upstream yields, a sediment budget approach is taken in this paper. The Lillooet River basin (3150 km^2 in area) offers an unusual opportunity for analysis because of the previous work of Slaymaker (1972, 1977, 1986), Gilbert (1972, 1973, 1975), Bovis (1982, 1990), and Jordan (1987). Nevertheless, it is recognized that the application of a sediment budget approach in a large complex basin such as the Lillooet is fraught with difficulty, has not been satisfactorily achieved elsewhere, and requires a number of simplifying assumptions.

SEDIMENT BUDGETS AND ROUTING

A sediment budget is "a quantitative statement of the rates of production, transport, and discharge of detritus" in a drainage basin (Dietrich *et al.*, 1982). Approximate sediment budgets have been constructed for a number of drainage basins, and have been used to make inferences about the relative importance, and linkages between, various transport and storage processes. Several of these are listed in Table I.

The difference between sediment budget studies and simple determinations of sediment yield is that in the former, sediment is routed from its sources, through various storage reservoirs, to the basin outlet. The basic equation describing sediment routing with respect to a particular storage reservoir and over a specific time increment is:

$$I = O + \Delta S$$

where I is input, O is output, and ΔS is change of storage of sediment in that particular reservoir. In practice, a watershed must be broken down into many reservoirs, and to quantify the lag times between input and output of sediment, the rates of transfer between active and less active reservoirs must be determined (Figs. 2, 5 and 6).

For a river channel system in a steady state (neither aggrading nor degrading; *i.e.* $\Delta S = O$), the residence time of sediment in a reach of the valley floor is given by

$$T = S / Q_s$$

where T is residence time, S is total storage volume, and Q_s is sediment discharge (for a steady state, $Q_s = I = O$). For computation, T and S may be defined on a unit valley length basis. Obviously, the residence time is highly dependent on the volume chosen for less active storage reservoirs; it could be very long if large, inactive, alluvial valley fills were included.

As Dietrich *et al.* (1982) point out, the residence time may be a poor indicator of how long most sediment takes to pass through a system. They also point out that the average age of

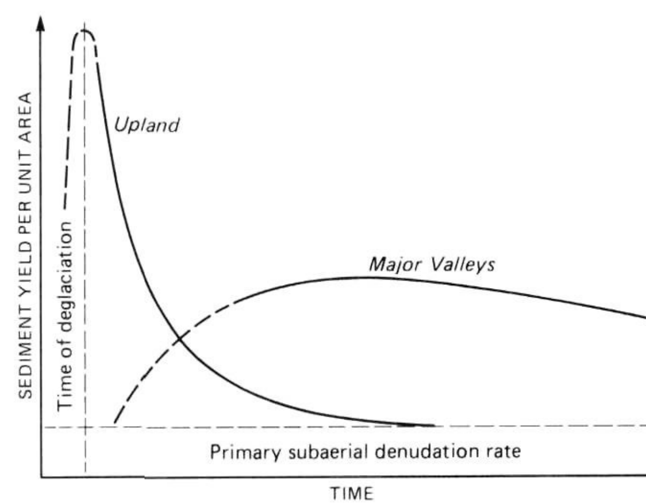

FIGURE 1. The paraglacial sediment cycle (Church and Slaymaker, 1989). This model was proposed to explain the downstream increase in sediment yield in many British Columbia river basins.

Le cycle sédimentaire paraglaciaire (Church et Slaymaker, 1989). On a proposé ce modèle pour expliquer l'augmentation de l'apport de sédiments en aval de nombreux bassins versants de la Colombie-Britannique.

1. One Bubnoff unit (B) equals one $m^3\ km^{-2}\ a^{-1}$, or one mm per 10^3 years, in terms of bedrock volume (Fischer, 1969).

sediment in any one storage element, such as a gravel bar, is highly dependent on the history of deposition and erosion of that element.

Dietrich and Dunne (1978) described sediment transfer rates and storage as power functions of basin area and length. This approach requires that sediment production and transport, and the morphometry of the drainage net, be reasonably homogeneous over the watershed. Their study was conducted in an unglaciated, fluvially dissected basin, developed in weathered bedrock, in a humid temperate climate. Of their calculated denudation rate of 33.5 B, about 60% was due to dissolution; residence times in alluvial reservoirs ranged from a few decades to 10 000 years, the latter applying to the main valley floor.

Several studies in northern California have used a sediment budget approach to investigate the response of a basin to, or its recovery from, disturbances resulting from extreme mete-

TABLE I

Some sediment routing studies from the literature

Author	Location	Basin area (km^2)	Drainage density (km^{-1})	Sediment yield ($m^3km^{-2}a^{-1}$)
Lehre (1982)	Lone Tree Cr, California	1.74	6.21	275
Roberts and Church (1986)	Queen Charlotte Islands, B.C.	3.9-12.6 (4 basins)	4.2-6.7	–
Dietrich and Dunne (1978)	Rock Cr, Oregon	16.2	4.0	33.5
Madej (1982)	Big Beef Cr, Washington	23	2.5	70
Benda and Dunne (1987)	Knowles Cr, Oregon	52	4.6	–
Kelsey (1982)	Van Duzen R, California	575	–	970
Madej (1987)	Redwood Cr, California	720	–	975

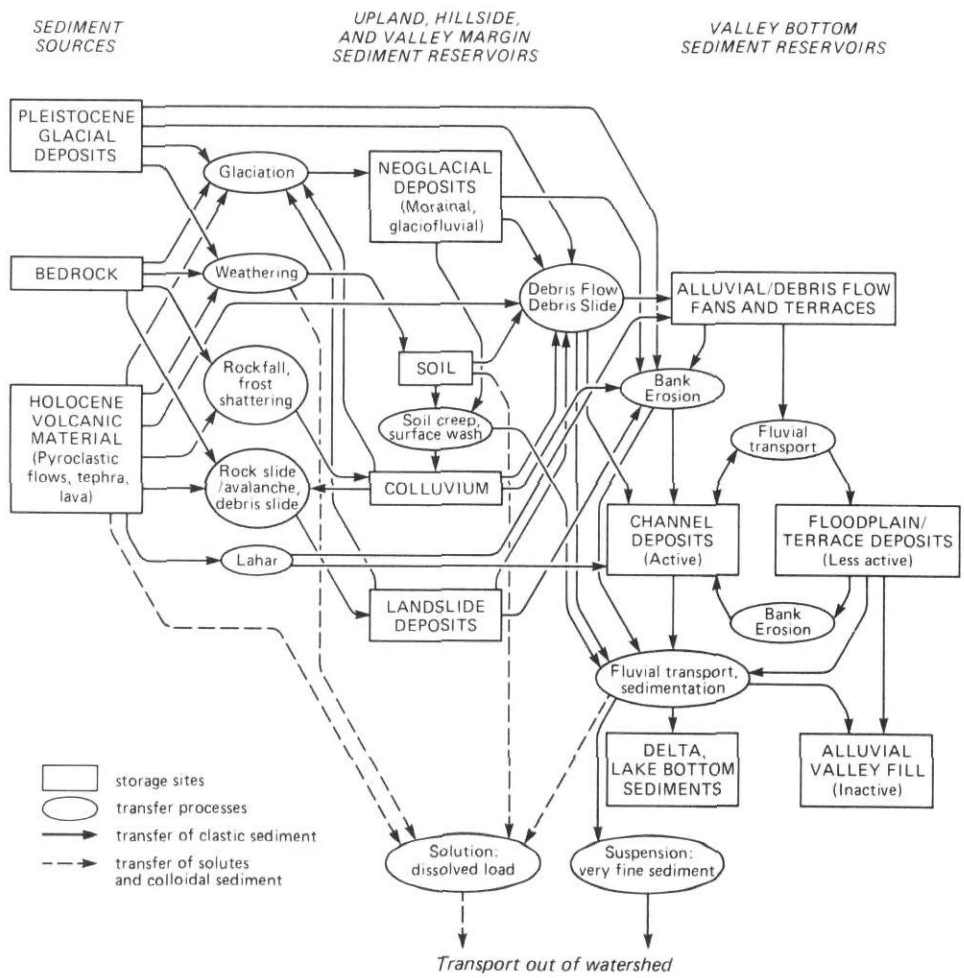

FIGURE 2. A conceptual model for Holocene sediment transfer in a glaciated, tectonically active, mountain watershed. The model is based on Lillooet River, which has experienced Holocene volcanism and glaciation, and which has a lake at the basin outlet.

Modèle conceptuel de transfert de sédiments dans un bassin versant de montagne partiellement englacé, tectoniquement actif. Le modèle a été élaboré à partir du cas de la Lillooet River, où se sont manifestés volcanisme et glaciation à l'Holocène et qui comprend un lac à l'embouchure du bassin.

orological events (Kelsey, 1980, 1982; Madej, 1987). They found that most of the debris produced as a result of an extreme rainstorm was stored as alluvial channel deposits in the upper part of the watersheds, causing several metres of aggradation, and that the zone of aggradation migrated into further downstream reaches over a time scale of decades.

Roberts and Church (1986) found similar sediment storage reservoirs (which they termed "sediment wedges") formed as a result of bank erosion following logging along stream banks in small watersheds in the Queen Charlotte Islands. Although sediment discharge increased following the disturbance, residence times also increased, due to the storage of large volumes of sediment in the channels.

An understanding of the relative importance of continuous versus episodic sediment transfer processes in a watershed is critical in sediment budget studies (Swanson *et al.*, 1982). Dietrich and Dunne (1982) used steady-state approach, which ignored episodic effects; however, the studies in California and the Queen Charlotte Islands specifically examined basin response to episodic processes. If sediment is supplied by events with relatively long recurrence intervals (for example, by infrequent large landslides), then the episodic nature of sediment transfer must be considered in any model. Selection of a time scale for the calculation of a sediment budget, and dealing with the short and probably unrepresentative time available for data gathering, are major problems.

Several difficulties must be considered in applying the approaches used in these sediment budget studies to a large, glacierised, and mostly inaccessible basin such as Lillooet River. First, the data requirements of sediment budget studies make them highly labour-intensive. The largest basin of those previously studied, Redwood Creek, involved a major investment in research and data gathering. Second, previous studies have not dealt with glacierised basins; as pointed out by Church and Ryder (1972) and by Church and Slaymaker (1989), the sediment yield of a glaciated and glacierised basin such as the Lillooet is likely to be out of equilibrium with present denudational processes. Third, measurement of bedload transport on a large mountain river such as Lillooet River has never been seriously attempted, and is likely to be unfeasible, except at a lake delta where combined bedload and suspended load yield can be estimated. Finally, as will be shown below, sediment production in the basin is highly episodic, and a steady-state model not only cannot be applied, but cannot be considered as a "normal" state.

Figure 2 provides a framework for sediment budget calculations, identifying the major sediment sources, transfer processes, and storage sites which need to be considered. In this figure, the primary sediment sources are considered to be bedrock and surficial deposits (the latter almost entirely due to Late Pleistocene glaciation and deglaciation) as they existed at the close of the Pleistocene period, as well as rock material added to the basin by Holocene volcanism. Sediment transfer processes which occur under Holocene climatic conditions constitute the remainder of the figure.

FIGURE 3. Location of Lillooet River watershed.
Localisation du bassin versant de la Lillooet River.

LILLOOET RIVER BASIN

Lillooet River drains an area of about 3150 km^2 in the southern Coast Mountains of British Columbia (Fig. 3). The geology, geomorphology, and hydrology of the basin have been described by Gilbert (1975) and by Jordan (1987). The basin as defined here includes the combined drainages of the Lillooet and Green Rivers above Lillooet Lake. Figure 4 shows the drainage system. Approximately 500 km^2, or 16%, of basin is glacierised, and according to Gilbert (1973), in the non-glacierised area drainage density is 1.0 km^{-1}. The mean elevation is approximately 1580 m and about half the basin is above timberline. The greatest local relief (mountain top to adjacent valley) is 2500 m, but average local relief is typically 1500 to 2000 m.

For its lowest 70 km, Lillooet River flows in an alluvial channel which progresses from braided and cobble-gravel bedded in its upper parts to meandering and sand-bedded near its mouth. The valley flat varies little in width throughout this length. Except for the extreme upstream end, there are no terraces along the valley. This observation, combined with other factors discussed below, suggests that the river is aggradational throughout the length of the valley, and may have been so through most of Holocene time. Pleistocene glacial valley fill deposits are remarkably absent from most of the main valley; typically, steep bedrock slopes with only a thin colluvial or morainal veneer meet the floodplain at an abrupt angle. In this respect, Lillooet valley is similar to many other deep, fiord-like valleys developed in resistant rock in the Coast Mountains. Thick Pleistocene deposits are found in limited areas of the basin, for example Green River valley and the mouth of Pebble Creek. In alpine areas, average slopes are gentler, and glacial deposits, many of them Neoglacial, are more widespread.

The sediment yield of Lillooet River basin was first estimated by Slaymaker (1972), who used the rate of advance of the river delta as shown by air photos since 1948, and by maps for 1858 and 1913. Gilbert (1972, 1973) combined these results with observations of sedimentation in Lillooet Lake. This method provided a combined yield for suspended load and bedload.

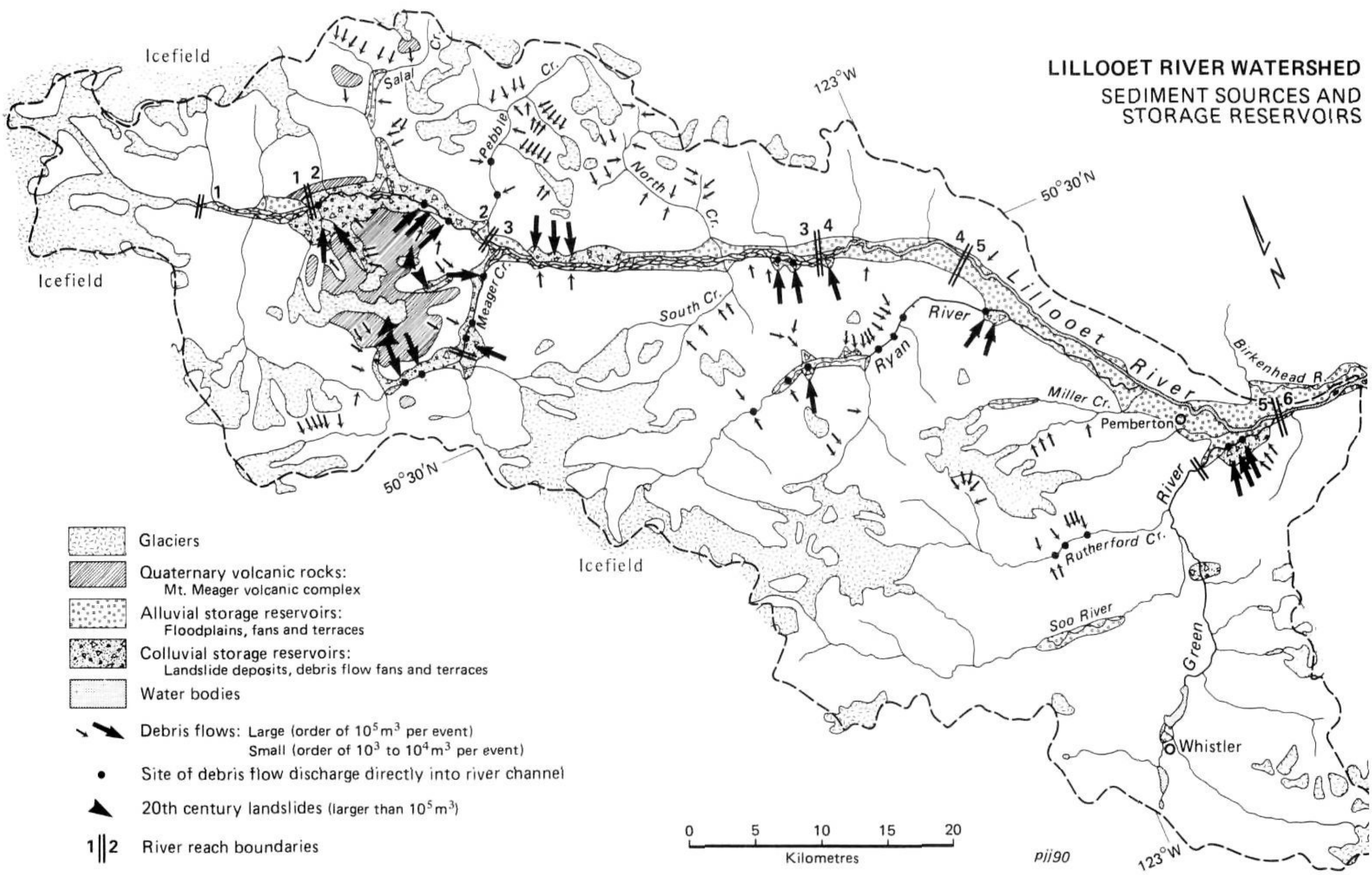

FIGURE 4. Map of Lillooet River watershed, showing principal sediment sources and storage reservoirs.

Carte du bassin versant de la Lillooet River, montrant les principales sources de sédiments et les lieux de stockage.

Slaymaker and Gilbert (1972) estimated that there was an increase in sediment yield of approximately three to four times after 1948, based on the rate of delta advance, which from 1858-1948 averaged 7.3 m a^{-1} (Table V). This was attributed to land use changes in the basin, in particular extensive river training and floodplain reclamation in the lower 30 km of the valley. Gilbert (1973) estimated the average clastic sediment yield of the entire 3800 km^2 basin draining into upper Lillooet Lake, from 1913 to 1969, to be 1.1×10^6 m^3 per year (solid rock basis), equivalent to a specific denudation rate of 290 B. Dissolved sediment yield is estimated to be an additional 0.23×10^6 m^3 per year, or 73 B (measured on the Lillooet River at Pemberton; Slaymaker, 1987). Suspended sediment measurements on the adjacent Birkenhead River showed that this river contributes a negligible proportion (about 1%) of the sediment supplied to the delta. Recently, Hickin (1989) has provided summary sediment flux data for the nearby Squamish River which are generally consistent with and of the same order of magnitude as the data for Lillooet River.

If Birkenhead River and other minor drainages are excluded, the long-term clastic sediment yield for Lillooet River is 344 B, and the total yield (including the dissolved component) is 417 B. The rate of delta advance from 1913 to 1948, 8.1 m a^{-1}, is about 59% of the average rate of advance from 1913 to 1969 (from data in Gilbert, 1972). For the periods 1913-1948 and 1948-1969, the clastic yield figures are respectively 203 B and 578 B.

SEDIMENT TRANSPORT, SOURCES, AND STORAGE

In the following sections, estimates of production from sediment sources are based on a reconnaissance inventory of mass movement in the basin (Jordan, 1987), and on results for other areas from the literature. These estimates are compared with the sediment yield of the basin from 1913 to 1948 as reported by Gilbert. The highly episodic nature of sediment production in the basin headwaters, and the residence time of sediment stored there in colluvial deposits as well as in the main valley floodplain, indicate that a time scale in the order of a thousand years should be used for sediment budgeting purposes. The use of a yield determined for 90 years to represent a period in the order of 1000 years is quantitatively imprecise, but these are the best data available.

The specific gravity of rock in the basin is assumed to be 2.65, and for calculating sediment volumes, a dry bulk density of 1.6 Mg m^{-3} is used for all deposits. (The sources in Table I used bulk densities ranging from 1.1 to 1.9.) The corresponding porosity is 40%. The bulk sediment yield to the delta, corresponding to the pre-1948 yield of 203 B, is thus 1.1×10^6 m^3. All sediment volumes in the following sections are reported as bulk volumes unless otherwise noted. To convert to equivalent solid rock volumes, the bulk volumes can be multiplied by 0.60.

CREEP

Average rates of soil creep combined with tree throw for shallow forest soils in mountainous environments are typically in the range of 2 to 5 mm a^{-1}, over a depth of 0.5 to 1 m (Slaymaker and McPherson, 1977; Dietrich and Dunne, 1978; Madej, 1982; Roberts and Church, 1986). In Lillooet basin, an average value near the low end of this range might apply, since unweathered bedrock is exposed or lies very near the surface on many slopes. Also, many slopes are decoupled from the channel system, leading to more or less permanent storage at the foot of slopes of the material produced by creep.

A drainage density of 1 km^{-1} is assumed for the basin (after Gilbert, 1973). Measurements on one tributary basin (North Creek), using 1:50,000 maps and air photos, give a drainage density of 0.8 km^{-1}. Hart (1979), using air photos, measured a drainage density of only 0.25 km^{-1} in forested areas and 0.1 in alpine areas of a tributary of Ryan River. A drainage density of 1 km^{-1}, therefore, is more likely an overestimate than an underestimate.

Using this drainage density, a creep rate of 2 mm a^{-1} over a depth of 0.5 m, applied over 50% of the drainage area (the rest being non-contributing slopes, bedrock, or glaciers), gives a sediment yield of about 3×10^3 m^3 a^{-1}. This is only about 0.25% of the total yield. Even if a much higher estimate of creep rate were used, the yield would still be negligible. This low yield is due to the low drainage density of the basin.

Another process which may be important in high mountain environments is "sackung" or deep rock creep (Eisbacher and Clague, 1984). There are about 30 km (measured as length along the valley axis) of apparently active sagging slopes in the basin, as indicated by such features as tension cracks and uphill-facing scarps. Rates of creep are generally unknown. Bovis (1990) measured rates of up to 50-100 mm a^{-1} at an unusually active site in the Mount Meager volcanic complex. If a more conservative estimate of 1 mm a^{-1}, over an average depth of 100 m, is assumed, then the total downslope movement in the basin, across the base of the sagging slopes, would be about 3×10^3 m^3 a^{-1}, the same as that estimated for soil creep. Sediment from sagging slopes can be routed to river channels through talus production, debris flows, or rockslides, all of which are more abundant on sagging slopes than elsewhere, as well as by bank erosion. In that large debris flows and landslides are dealt with separately, debris production from sagging slopes is double-counted here to some extent.

DEBRIS FLOWS

Recent studies in the U.S. Pacific Northwest (*e.g.* Swanston and Swanson, 1976; Kelsey, 1980; Benda and Dunne, 1987) have emphasized the importance of debris slides and debris flows in routing sediment from weathered bedrock on hillslopes to stream channels. In the glaciated Coast Mountains, where residual soils are lacking, the environment of debris flows is somewhat different. Here, debris flows are a prominent feature of many steep, first and second order channels, and many of them originate in alpine areas. Debris flows in the Coast Mountains are an important mechanism for routing sediment from talus deposits, other alpine colluvial deposits, and Neoglacial morainal deposits to valley bottoms, via small steep stream channels.

An inventory has been made of major debris flow channels in the Lillooet basin, using air photos at a scale of about 1:50 000, combined with field checking in some areas (Jordan, 1987). The distribution of these debris flow channels is mapped on Figure 4.

The frequency of debris flows in many of these channels is high, probably in the order of at least one per decade (Jordan, 1987). Most channels appear fresh on air photos and in the field, with little vegetation in the channels or on recent deposits. A high proportion of debris flow channels were active in a 1984 rainstorm, which was about a 20-year rainfall event. A large debris flow at the mouth of Ryan River valley was observed to be active in 1975 (Hart, 1979), and again in 1984. In Meager Creek valley, some channels have carried two or three large debris flows since 1980. Although some debris flow channels may become inactive at times, many other channels not identified on air photos as presently carrying debris flows, may become active at other times.

Typical magnitudes of debris flow deposits observed on air photos and in the field range from about 5000 m^3 for the smallest ones identified, to several larger than 100 000 m^3. A large number of smaller debris flows probably occur, either more frequently in channels dominated by larger flows, or in channels too small to identify on 1:50 000 air photos.

In most cases, debris flows discharge onto the upper part of colluvial or composite alluvial-colluvial fans, with a relatively small proportion of the debris being delivered directly to the channel system. An unknown proportion of the stored material is later reworked by fluvial action and routed to channels downstream. As many colluvial fans are large, much of the debris may go into long-term storage. This is particularly true for debris flows developed in resistant granitic rocks, which contain a high proportion of boulders. Some other debris flows, as a result of the geometry of fans and valley, or due to the mobile nature of fine-grained volcanic debris, frequently deliver their material directly to higher-order stream channels. These locations are marked on Figure 4.

To estimate the sediment production from debris flows, the debris flow sites on Figure 4 were counted in each sub-basin, and average magnitudes and frequencies were assumed to apply. These assumed values provide an order of magnitude estimate of sediment supplied from major debris flow channels. For "small" debris flows, an average yield of 20 000 m^3 every 10 years, 25% of which is delivered to the channel, was assumed. For "large" debris flows, an average yield of 50 000 m^3, at the same frequency, was used. Where site specific information is available for particular debris flows, this was used to make better estimates. The sediment yield estimates are tabulated in Table II, and are given as a range of volume totals. The smaller total includes only the volume assumed to reach the channel directly (which implies the debris fans are aggrading), while the larger total includes the total estimated debris flow volume (which implies that the debris fans are in equilibrium over the long term, and eventually deliver all their stored debris to the channel system).

LANDSLIDES AND OTHER MAJOR MASS MOVEMENTS

Unlike the weathered unglaciated mountains in the U.S. Pacific Northwest, and the more maritime parts of the Coast and Insular Mountains of British Columbia, debris slides on forested slopes do not appear to be a significant sediment source in the Lillooet basin. However, small debris slides along incised stream channels, at the base of talus slopes, and on Neoglacial moraines may be significant, and would be very difficult to inventory in a basin of this scale.

Large landslides, however, are a significant sediment source in the basin, especially in the Mount Meager volcanic complex. The highly episodic nature of these events makes routing of their sediment problematical. The major known events are listed in Table II, along with estimates of the amount of sediment they have contributed over various time scales.

To estimate the sediment contribution from landslides, the volume of the river incision into their deposits was estimated from 1:50 000 topographic maps. This, and estimates of total volume, are order of magnitude estimates only.

The largest single deposit is in upper Lillooet River valley, resulting from the explosive eruption and subsequent (or simultaneous) collapse of part of the Mount Meager complex 2350

TABLE II

Colluvial sediment source estimates

Volumes are given in $10^3\ m^3a^{-1}$, and include input to tributary streams.

River reach	Debris flows: total volume	Debris flows: delivered to channel	Landslides and lahars: 5000 years	Landslides and lahars: 100 years	Soil creep	Sackung	Other (channel incision, debris slides, surface wash, etc.)
1							
2	132	43	33	1			
3	52	17					
4	14	3					
5	92	26					
Meager	77	39	32	75			
Green	60	15					
TOTAL	427	143	65	76	3	3	?

Landslides and lahars: volume estimates in $10^6\ m^3$; annual yield estimates in $10^3\ m^3a^{-1}$

River reach	Date	Debris volume[1]: original event	Debris volume[1]: stored	Debris volume[1]: removed by river	Average annual yield[2]: Events in last 5000 years	Average annual yield[2]: Events in last 100 years
2	2350 BP	1000	850	150	30	
	900 BP	20 ?	6	14	3	
	1986	0.5	0.4	0.1		1
Meager	4000 BP	500	350	150	30	
	900 BP	50 ?	40	10	2	
	1931	5	1	4		40
	1940 ?	10	7	3		30
	1975	14	13.5	0.5		5
Green	1000 BP	30	30	0	0	
TOTAL					65	76

Notes: [1] All volumes are very approximate. Except for field observations of some recent events, volumes are estimated from 1:50,000 maps and air photos.

[2] Yield is calculated as volume removed, divided by the specified time period (not by the age of the event). Events in last 100 years are neglected in calculating yield for the 5000 year period.

years BP. The river is still actively cutting a canyon through the deposits, which include pyroclastic flow and tephra as well as landslide material. Similar deposits, of about half the volume, are found in Meager Creek valley; the basal deposit of this complex has been dated at 4000 years BP. At least four landslides with volumes in the order of 10^6 to 10^7 m^3 have occurred in the volcanic complex in this century, most notably the 1931 and 1975 Devastation Glacier landslides. Landslides of this scale thus appear to be a significant process over a time scale of about a century, and larger landslides, possibly related to periods of volcanic activity, are a significant process over time scales of several thousand years.

Two large volcanic debris flows (also known as "lahars") are known to have descended low-gradient valleys in the last 1000 years. One of these resulted from the 1931 Devastation Glacier landslide, and is conservatively estimated, by extending the level of terrace remnants across the valley, at 5×10^6 m^3. A larger debris flow of unknown origin flowed into upper Lillooet valley 900 years BP; about 6×10^6 m^3 of debris remain in the floodplain. These highly fluid debris flows are unusual in that they deliver a high proportion of their sediment almost instantaneously to the channel system. It is likely that similar, probably larger, lahars descended Lillooet River valley as a result of the 2350 years BP eruption; such lahars were a prominent feature of the 1980 Mount St. Helens eruption (Janda *et al.*, 1981).

Landslide sediment yield volumes averaged over two time scales, 5000 years and 100 years, give similar totals of about 70×10^3 m^3/y. This figure is therefore assumed applicable, for purposes of computation, to any long-term time scale, even though sediment delivery to the river from the largest landslides must be extremely episodic.

GLACIERS

Direct measurements of sediment yield from glaciers in Lillooet basin have not been made. Reference can be made to suspended sediment yields from other locations, but bedload material volume is essentially impossible to estimate. Sediment yield would depend on the erodibility of the rock (which ranges from very low over most of the basin to very high in the volcanic area), and on the level of activity of the glaciers (high in this maritime climate).

Church and Ryder (1972) give total clastic sediment yields in the order of about 200 B for several basins in the Canadian Arctic and Scandinavia; reported values range from 54 to 571 B, for basins with 12 to 75% glacier cover. Church *et al.* (1989) report sediment yield values in the range of about 100 to 500 B for glacier-dominated basins in British Columbia, although the higher-yielding basins (in the Stikine River basin) include Quaternary volcanic rocks. In Lillooet basin, Slaymaker (1977) estimated a yield of 13 B for upper Miller Creek, although a lake traps much of the glacial sediment produced in this basin. Slaymaker and Gilbert (1972) estimated a yield of 0.15 to 0.30×10^6 Mg a^{-1} from Lillooet basin (equivalent to about 18 to 36 B), based on values from the literature and on an estimated glacier-covered area of 400 km^2.

For this paper, considering the overall glacier cover of about 16% and the fact that small lakes trap sediment below many glaciers in the basin, an average yield in the range of 20 to 100 B was chosen as reasonable. This would give a basin yield in the range of 100 to 500×10^3 m^3 a^{-1} on a bulk volume basis. In Table III, this yield is divided amongst the sub-basins in approximate proportion to the area of glacier cover in each.

BANK AND SURFACE EROSION

Bank erosion is one of the principal means by which sediment from hillslopes or alluvial storage reservoirs is mobilized into the channel system. In alluvial reaches, almost all sediment contributed by bank erosion is material previously stored in alluvial reservoirs such as floodplain and bar deposits. For a river channel which is not changing in average width, bank erosion at one location will be balanced by deposition in bars or on floodplains elsewhere.

Where an active channel is in contact with a hillslope or other non-alluvial deposit, bank erosion may contribute material previously derived from soil creep, other colluvial processes such as landslides and debris flows, or recent glacial deposi-

TABLE III

Summary of sediment sources

Volumes in 10^3 m^3a^{-1} (bulk basis), except last column. Soil creep and other minor sources are neglected.

River reach	Contributing area (km^2) cumulative	Contributing area (km^2) to reach	Debris flows (range)	Landslides (range)	Glaciers (range)	Total	Mean	Denudation ($m^3km^{-2}a^{-1}$ or B)
1	410	410			30-150	30-150	90	132
2	770	360	43-132	0-35	15-75	58-242	150	250
Meager		300	39-77	30-75	10-50	79-202	141	281
3	1470	400	17-52		10-50	27-102	64	97
4	1580	110	3-14			3-14	8	44
5	2220	640	26-92		15-75	41-167	104	98
Green		880	15-60		20-100	35-160	98	66
6	3150	50						0
TOTAL		3150	143-427	30-110	100-500	273-1037	655	125

tion. The yield of material from these sources has been estimated separately, as described in the sections above.

Where a channel is actively cutting into bedrock or Pleistocene glacial deposits, "new" material not accounted for in the preceding sections will be contributed to the channel. In the aggrading channel of Lillooet River, this source of material is of negligible importance; however, in the incised channels of many of the tributary streams in the watershed, it may be a significant source of sediment. Present rates of bank erosion and downcutting in these streams are entirely unknown, and no attempt has been made to estimate contributions from this source in this paper. However, since Pleistocene glacial deposits are not extensive in valley bottoms in this watershed, the yield is probably much less than for many other British Columbia rivers, especially those discussed in Church and Slaymaker (1989).

Surface wash into channels from areas of bare soil is an additional possible sediment source which has not been estimated. Because of the heavy forest cover and low drainage density, this process is unlikely to be a significant source on a watershed scale, although it is important in some alpine areas (Jones, 1982). Surface wash is probably more important in areas affected by logging and agriculture. Before 1948, sediment from these activities was negligible; however, since 1948, sediment production from logged and cultivated areas may have increased significantly (Slaymaker and Gilbert, 1972; Hart, 1979).

SEDIMENT TRANSPORT AND ATTRITION

Figure 5 illustrates a conceptual outline of a possible model of sediment transport which might apply to an arbitrary reach of Lillooet River. The sediment yield measurements at the delta provide long period integrated sediment transport totals. But little is known about sediment transport rates in the river, and nothing is known about bedload transport rates. What is known, is that sediment discharge at the delta consists mainly of sand and finer material, with a minor amount of small pebbles (Gilbert, 1973), while the river in its upper reaches is dominated by cobble-sized gravel. Grain size analyses of debris flow deposits at Meager Creek show that the granitic-source debris flows are typically about 85% bedload sized material, while for those of volcanic source the proportion is about 75%. (0.5 mm is taken as the division between suspended load and bedload material.)

The proportion of sand to gravel in the river can increase downstream either through abrasion, or through differential sorting. Abrasion of the volcanic material probably takes place rapidly. However, granitic rocks, which underlie most of the watershed and dominate the bedload in the main Lillooet River valley, are highly resistant to abrasion and breakage. The alternative fate of the abundant coarse gravel of the upper river is that it is stored, more or less permanently, in the upper reaches. If this is the case, then the sediment transport rate of the river, per unit water discharge, must decrease downstream, and the channel must be aggrading.

Brierley and Hickin (1985) examined the downstream reduction of bed material size in the nearby Squamish River, which is similar in morphology and sediment regime to Lillooet River.

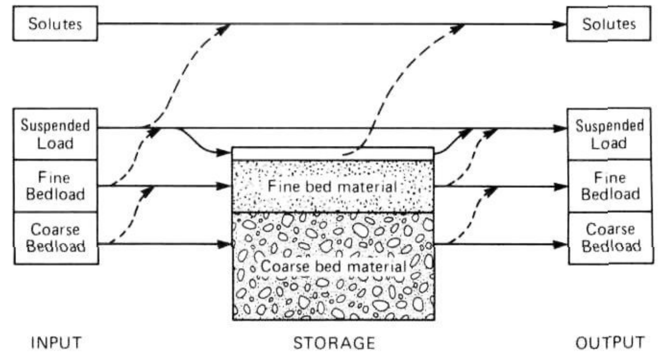

FIGURE 5. A general model for sediment routing through a river reach. The dashed lines show attrition of sediment.

Modèle de l'acheminement des sédiments dans un bief. Les lignes tiretées illustrent l'attrition des sédiments.

They concluded that differential sorting was more important than abrasion.

SEDIMENT STORAGE

To estimate storage of sediment in alluvial reservoirs, the river system is divided into reaches of similar morphology (Fig. 4). On Lillooet River, reach 1 and 3 are cobble-gravel, braided channels, reach 4 is transitional, with finer gravel and a shifting, split form, and reach 5 is irregularly meandering with a sand and pebble-gravel bed. Reach 6 is a straight to sinuous, sand bed, delta reach. Reach 2 is incised for most of its length. Slope and channel dimensions are summarized in Table IV.

To estimate channel and floodplain storage, the depth of these storage reservoirs is assumed to be equivalent to the estimated average thalweg depth of the channels. Depth for the braided reaches is based on the relief of bars and channels from surveying on the floodplain of Meager Creek, while depth for the lower reaches is based on channel surveys by the British Columbia government following the 1984 flood (Nesbitt-Porter, 1985); 0.5 m is arbitrarily added to these depths to allow for scour. Channel sediment cross-sectional area for a reach is taken to be the average channel width times the depth, subtracting the approximate cross-sectional area required to pass the bankfull flood. Floodplain sediment volume is calculated in a similar way.

In the absence of other information, the active storage volume of alluvial fans is assumed to be the product of the fan area and an arbitrary channel depth of 2 m, regardless of whether a fan is presently aggrading or degrading. Total fan volume would be less meaningful, as some fans may be largely relict from the early Holocene, and the fan volume buried below river floodplain level is unknown.

The underlying alluvial fill of the valley is assumed to be inactive, and is not included in the calculation of active storage. The accumulation of this fill is accounted for by the estimated rate of aggradation (see following paragraph and Figs. 6 and 7). It is interesting to note that, if a uniform cross-section is assumed for the valley, the total volume of the valley fill is in the order of 10×10^9 m^3. If the estimated sediment yield at the delta is representative of sediment production from the

TABLE IV

Estimated storage volumes

River reach	Average Dimensions					Estimated Storage (10^6 m^3)					
	Length (km)	Channel width (m)	Floodplain width (m)	Channel depth (m)	Floodplain slope	Channel	Floodplain	Fans	Fluvial terraces	Debris flow terraces	Landslides
1	9	300	900	2.5	.007	5	14	1			
2	16	(var)	(incised)	?	(var)	2	1	17	20	6	850
3	21	300	1000	3.5	.006	16	51	9	5		
4	15	200	1400	4	.0025	7	72	4			
5	27	120	1500	5	.0009	6	186	7			
6	8	180	1600	5	.0006	3	57	2			
Meager	9	(var)	(var)	2.5	.03	2	1	6		2	410
Green	8	60	(var)	3	.005	1	7	4			30
TOTAL						42	389	50	25	8	1290
Years sediment yield from basin[1]						38[2]	350[2]	45	23	7	1170

Notes: var = variable.

[1] Estimated storage in reservoir, divided by 1.1 × 10^6 $m^3 a^{-1}$, the average sediment yield measured at the delta. This is not necessarily a residence time, but a measure of how much sediment is stored in that particular reservoir.

[2] In the case of the main valley and floodplain, these figures approximate a residence time, since all coarse sediment passes through these reservoirs.

basin over the entire Holocene period, this would be the equivalent of about 10 000 years of sedimentation.

Figure 6 gives a conceptual diagram of sediment storage in channel (active), floodplain (less active), and inactive reservoirs. In the third model, the volume of the inactive reservoir is constantly growing as the floodplain aggrades. Figure 7 shows two models for estimating possible floodplain aggradation. In order for the channel slope to be preserved as the delta advances, aggradation must take place upstream. The least amount of aggradation would be given by the first model, in which aggradation in the delta reach (the product of the rate of delta advance and the floodplain slope) is applied along the length of the valley. However, this would result in the low-gradient delta reach extending in length, while the other reaches remain constant in length. Because of differential sorting and deposition of coarse bed material, the upper reaches should extend in length as well. The second model assumes that the length of each reach except the furthest upstream remains constant, and results in greater rates of aggradation for the upper reaches. However, this model assigns all the increase in length to the braided upstream reach. The most likely pattern of aggradation probably is between the two extremes, which bracket a range of aggradation of 0.4 to 1.6 × 10^6 $m^3 a^{-1}$. This rough calculation suggests that aggradation in the river valley is comparable in order of magnitude to sediment yield at the delta, and is perhaps 0.5 to 1 times as great as the latter.

Since about 1948, river diking and lowering of the lake level have prevented most floodplain aggradation in the lower 35 km of the valley. However, significant aggradation in parts of the floodplain occurred during the 1984 flood, when the dikes were breached.

THE UNBALANCED SEDIMENT BUDGET

Table III gives a summary of sediment sources in the basin which have been accounted for in this inventory. Volumes are given as ranges, based on the ranges assumed for debris flow and glacier contributions. The total sediment supply from inventoried sources is in the range of 0.3 to 1.0 × 10^6 $m^3 a^{-1}$.

Sediment yield at the delta has been measured at 1.1 × 10^6 $m^3 a^{-1}$, and the estimated positive change in alluvial storage in the order of 1 × 10^6 $m^3 a^{-1}$ means that the sediment supply to the valley should be at least 2 × 10^6 $m^3 a^{-1}$. Even if the upper limit of the sediment supply estimate is used, the estimate of sediment supply is short by about 10^6 $m^3 a^{-1}$. This budget deficit implies serious underestimation of colluvial or glacial sources, or both.

THE SEDIMENT REGIME AFTER 1948

Between 1946 and 1951, to reclaim areas of the floodplain and control river flooding, 14 km of river cutoff and 38 km of dykes were constructed in the meandering reach of the river, shortening the channel by 5.5 km and increasing its gradient (Slaymaker and Gilbert, 1972). In 1952, the level of Lillooet Lake was lowered by 2.5 m. These changes were followed by rapid downcutting and bank erosion along parts of the river channel, and by an increase in the rate of delta advance (Gilbert, 1973). Approximately 2 × 10^6 $m^3 a^{-1}$ of additional sediment, or about 40 × 10^6 m^3 over the 1948-1969 period, is needed to explain the increased rate of delta advance. Slaymaker and Gilbert (1972) suggested that river engineering works and logging were the most likely sources. First-approximation estimates of possible sediment supply from logging (based on figures in Swanston and Swanson, 1976, and

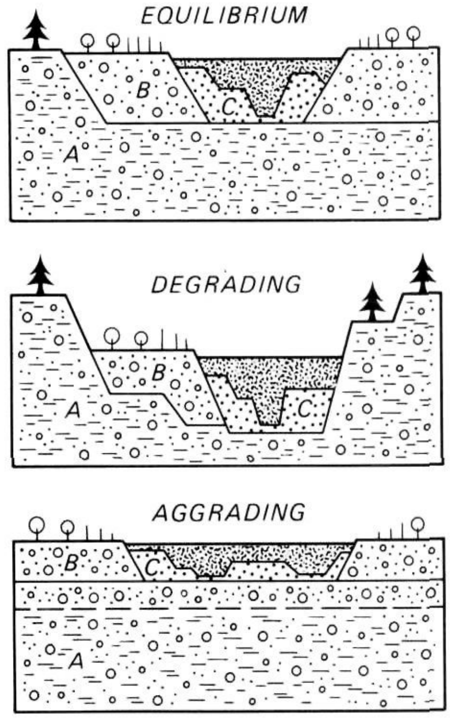

FIGURE 6. Sediment storage in river channel alluvium, for rivers which are in equilibrium, are degrading, or aggrading. In the bottom diagram, sediment is transferred to reservoir "A" from the more active reservoirs as aggradation proceeds. A = "permanent" or inactive storage — residence time approaches infinity; B = floodplain or less active storage — long residence time; C = channel or active storage — short residence time.

Stockage de sédiments dans les alluvions du chenal, dans une rivière en équilibre, en voie de déblaiement et en voie de remblaiement. Dans le diagramme inférieur, les sédiments sont transférés au réservoir A à partir des réservoirs plus actifs avec la progression du remblaiement. A = stockage permanent ou inactif; B = plaine d'inondation ou stockage moins permanent; C = chenal ou stockage provisoire.

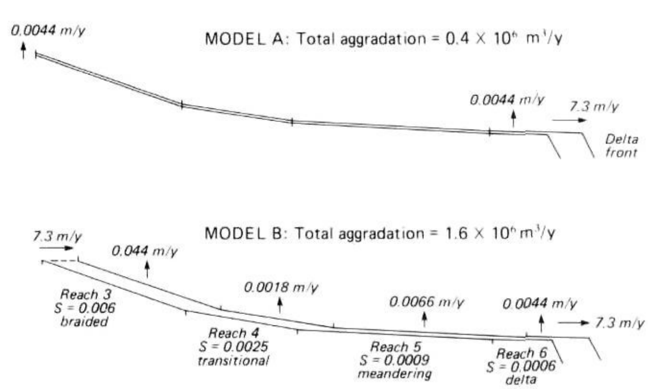

FIGURE 7. Models of aggradation in Lillooet River valley. The two models show the lower and upper limits of the rate of aggradation that would be necessary to preserve channel slope as the delta advances.

Modèles de remblaiement de la vallée de la Lillooet River. Les deux modèles illustrent les limites inférieure et supérieure de la vitesse de remblaiement nécessaire pour conserver la pente du chenal au fur et à mesure de la progression du delta.

a logged area of 3% of the basin given by Nesbitt-Porter, 1985) suggests that logging could account for only a minor portion of this volume.

Alternative possible sources might be increased sediment yield during the period of retreat of glaciers from their Neoglacial maxima from the 1920s through the 1960s, or a pulse of sediment from the 1931 Meager Creek debris flow (or other large undocumented slope failures in the volcanic complex). If these sediment inputs were delayed by several decades in the upper part of the valley (which is reasonable considering the residence times indicated in Table IV), then they could have reached the delta after 1948.

The recent position of the delta is shown by a 1986 air photo. The average rate of advance from 1969 to 1986 is calculated from this photo to be 14 m a^{-1}; Table V shows this calculation and Gilbert's earlier data. The steadily declining rate since the 1948-1953 period is consistent with a period of rapid downcutting and erosion following the lake level lowering and channel straightening, and a more gradual adjustment of the river in recent years. This suggests that engineering works were largely responsible for increased sedimentation after 1948. Contributions from Neoglacial retreat and major recent mass movement events in the Quaternary volcanics cannot be ignored but the resolution of the delta advance data is inadequate to provide a firm conclusion.

CONCLUSIONS

The estimated total supply from sediment sources in Lillooet River basin is only about half the magnitude necessary to explain the observed long-term average yield of clastic sediment from the basin. Floodplain aggradation in the main valley is a positive storage change which further increases the discrepancy.

The most important sediment sources are glaciers (and probably the adjacent stored deposits of Neoglacial sediment); debris flows, which are especially abundant and frequent in the Quaternary volcanic complex; and large landslides in the volcanic complex, the largest of which are related to volcanic eruptions. Soil and bedrock creep, and sediment from logging operations and agriculture, provide relatively smaller amounts of sediment. Bank erosion may be important along some incised

TABLE V

Rates of advance of Lillooet River delta

Period	Time (years)	Delta advance (m)	Mean annual advance (m a^{-1})
1858-1913	55	374	6.8
1913-1948	35	284	8.1
1948-1953	4.7	140	30
1953-1969	16.1	338	21
1969-1986	17.0	233	14

Notes: Data for 1858-1969 are from Gilbert (1973).
The rate of advance since 1969 is based on an air photo taken 4 August 1986.

tributary streams, but in the main river valley it serves only to redistribute previously deposited sediment.

Sediment inputs are highly episodic on several time scales. Many debris flow channels appear to experience flows every decade or so; thus they can be considered a continuous source when compared to the return periods of floods which are significant in sediment transport. Large volcanic debris flows, however, have return periods in the order of one to several centuries, and provide large single pulses of sediment, in the order of millions of cubic metres, to the channel system. Larger landslides in the volcanic complex, with return periods in the order of a thousand years or longer, must overwhelm the channel system with sediment when they occur, and remain significant sediment storage sites and sources for thousands of years. Periods of volcanic activity, with return periods of perhaps a few thousand years, are a major factor in episodic colluvial sediment delivery. Finally, engineering intervention has resulted in increased sedimentation at the delta in recent decades.

Retreat of glaciers from the Neoglacial maximum in the last century has probably provided an important sediment input in alpine areas of the basin, and sediment from this source routed through alluvial storage reservoirs may have contributed to the rapid advance of Lillooet River delta since 1948. However, the impact of engineering works on the lower river and delta since 1948 makes it difficult to identify changes in upstream sediment supply. The Late Pleistocene deglaciation provided an exceptional source of sediment, the storage and remobilization of which dominates sediment yield in many large watersheds in British Columbia (Church and Slaymaker, 1989). However, Pleistocene glacial deposits do not appear to be as significant a sediment source in the Lillooet basin as in many watersheds elsewhere in the province.

An alternative model to that of Church and Slaymaker (1989) which applies specifically to the Lillooet River watershed and takes into account the two additional major episodic sediment sources in the Holocene, namely volcanic and Neoglacial, is presented (Fig. 8). This model has the virtue of indicating where further work is needed so as to provide more quantitatively precise data on sediment sources and storage, and to direct attention to those processes which are most important in the long term Holocene evolution of the valley. Finally, the validation or refinement of the model will provide a basis for examining the true significance of human activity in accelerating sediment yield by forestry, agriculture, and river training works.

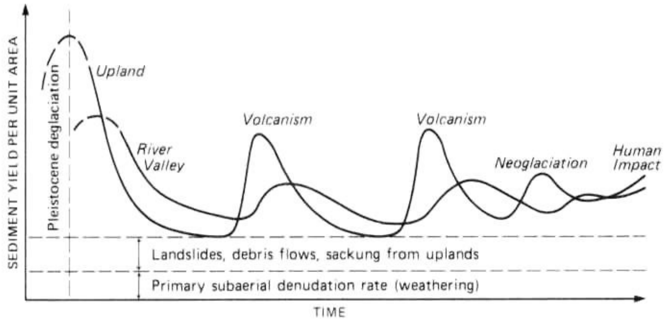

FIGURE 8. A model of Holocene sedimentation in Lillooet River valley, showing the effects of episodic sediment inputs on sediment yield. The figure is not to scale.

Modèle de la sédimentation dans la Lillooet River, à l'Holocène, illustrant l'effet des approvisionnements épisodiques en sédiments sur l'apport de sédiments. Le diagramme n'est pas à l'échelle.

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