Late Holocene sediment yields in small alpine and subalpine drainage basins, British Columbia

PHIL OWENS
Department of Geography, University of Exeter, Exeter EX4 4RJ, UK
OLAV SLAYMAKER
Department of Geography, University of British Columbia, Vancouver, British Columbia, Canada V6T 1Z2

Abstract It is generally supposed that specific sediment yield declines as the area drained increases. In British Columbia this hypothesis does not appear to apply and sediment yields increase at all spatial scales up to 3 × 10^4 km^2. This effect results from the dominance of secondary remobilization of Quaternary sediments along river valleys over primary denudation of the land surface in catchments larger than 1 km^2. The present study uses lake sediments to establish late Holocene sediment yields for three small catchments (less than 1 km^2) that straddle the alpine-subalpine ecotone (1620 to 1850 m above sea level) in the Pacific Ranges of the Coast Mountains of British Columbia. Sediment yields for the three catchments range from 0.005 to 0.220 t km^{-2} $year^{-1}$ and show an increase in yield with a decrease in elevation. The sediment yields established are orders of magnitude lower than regional rates for larger scale basins. These results are not inconsistent with the scale effects noted for the sediment yields of larger basins in British Columbia and confirm the existence of low yields in small pristine alpine and subalpine catchments.

THE CONVENTIONAL MODEL

At present, it is widely held that specific sediment yield – the quantity of sediment passing a monitored river cross section per unit area drained upstream of that section per unit time – decreases with increasing catchment area (Schumm, 1977; Milliman & Meade, 1983; Walling, 1983). This inverse relation between specific sediment yield and catchment area (Fig. 1) has been explained in terms of decreasing slope and channel gradients and increasing opportunities for deposition associated with increasing catchment size. A useful discussion of the variation of this relation for catchments of different spatial scales in different environments is provided by Walling (1983), who subsequently reviews many of the problems and limitations of relating on-site rates of erosion and soil loss within a catchment to the sediment yield at the catchment outlet.

There are, however, cases where this conventional model does not apply (e.g. Happ *et al.*, 1940; Douglas, 1967; Carson *et al.*, 1973; Neill & Mollard, 1982; Ashmore, 1986). For example, in the 360 km^2 Coon Creek basin in the

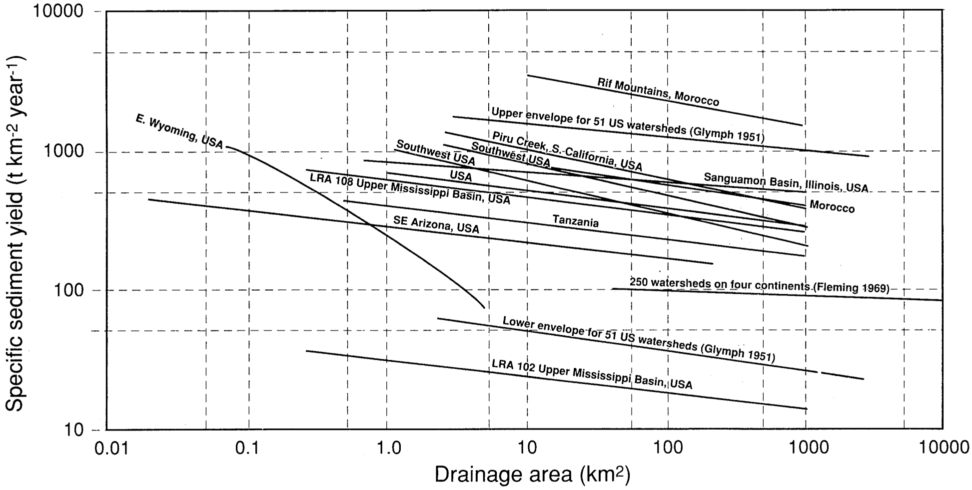

Fig. 1 The conventional model of specific sediment yield (based on Church *et al.*, 1989).

Driftless area of Wisconsin, USA, there was severe upland erosion during the late nineteenth and early twentieth centuries. Most of this sediment was deposited in river valleys and Trimble (1981, 1983) estimated, using a sediment budget approach, that only 5% of eroded material was removed from the catchment. Soil conservation measures in the 1930s reduced upland erosion, but sediment yield was not reduced accordingly due to the remobilization of sediment stored in valley-fill deposits. Consequently, contemporary sediment yield is poorly related to upstream erosion and the specific sediment yield increases downstream in many instances.

The conventional model also does not appear to work in glaciated British Columbia (Slaymaker, 1972, 1987; Church & Slaymaker, 1989; Church *et al.*, 1989). This paper reports on new and previous research on clastic sediment yield at different spatial scales in British Columbia, with particular reference to the Lillooet River system.

SEDIMENT YIELD IN BRITISH COLUMBIA: A REVIEW

In western Canada, recorded sediment and solute yields range from the equivalent of 3 to 1290 t km^{-2} year^{-1} (Slaymaker, 1987). Modal values for Canada east of the Cordillera are 3 to 130 t km^{-2} year^{-1}, except in those basins that are highly agriculturally disturbed or where urban land development is occurring. In the Cordillera itself the full range from 3 to 1290 t km^{-2} year^{-1} is experienced, but with modal values from 26 to 530 t km^{-2} year^{-1} (Slaymaker, 1987). The most intriguing observation is that the lowest yields in the Cordillera (3 to 26 t km^{-2} year^{-1}) occur in the unglacierized 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 3 t km^{-2} $year^{-1}$ when extrapolated to drainage basin scale (Caine, 1974; Slaymaker, 1977).

The model for British Columbia has been mainly developed for catchments greater than 1 km^2. The present study uses lake sediments to derive late Holocene sediment yields for three small unglacierized alpine-subalpine catchments less than 1 km^2 in the Coast Mountains. These catchments are believed to be representative of their respective altitudinal zones in southwestern British Columbia.

STUDY AREA AND METHODOLOGY

A detailed description of the study area and the methodology used can be found in Owens & Slaymaker (1992). Only the salient points will be described here. The lakes studied -- Gallie Pond, Middle Lake and Ash Lake (50°24'N 122°57'W) – straddle the alpine-subalpine ecotone, approximately 120 km north of Vancouver, British Columbia, in the Pacific Ranges of the Coast Mountains (Fig. 2). The alpine zone is here defined as the altitudinal zone above the upper limit of continuous forest or above the timberline (Löve, 1970). Table 1 describes the morphometric characteristics of the lakes during the summer of 1989. The present mesoscale climate is cold perhumid and annual precipitation exceeds 1800 mm. The local bedrock consists of the Late Cretaceous Gambier Group metasediments and quartz diorite of the Coast Plutonic Complex. The vegetation is areally dominated by alpine tundra with some tree islands at the elevation of Gallie Pond and more continuous stands of conifers (mainly mountain hemlock) around Ash Lake.

To define the spatial variability of sedimentation in the lakes, several sediment cores were collected from each lake. In total, 56 cores were collected: 23 from Gallie Pond, 16 from Middle Lake and 17 from Ash Lake. Core correlations and chronology were established by the presence of Bridge River tephra which was identified using criteria described in Reasoner & Healy (1986) and radiocarbon dated at *c.* 2350 years BP (Read, 1977). This enabled sediment accumulation per unit time to be calculated. A comprehensive lake sediment budget was developed to assess the relative contributions from various sources. Corrections were made for non-catchment eroded material (organic matter, biogenic silica, lake bank material and regional aeolian dust) and for outflow losses (see Owens & Slaymaker, 1992). No contemporaneous assessment was made of solute fluxes, though earlier work on Gallie Pond has estimated the general magnitude of these at *c.* 3 t km^{-2} $year^{-1}$ (Slaymaker, 1987), several orders of magnitude greater than the clastic sediment flux.

LAKE SEDIMENT-BASED SEDIMENT YIELDS

Table 2 shows that the corrected sediment yield for each catchment ranges from

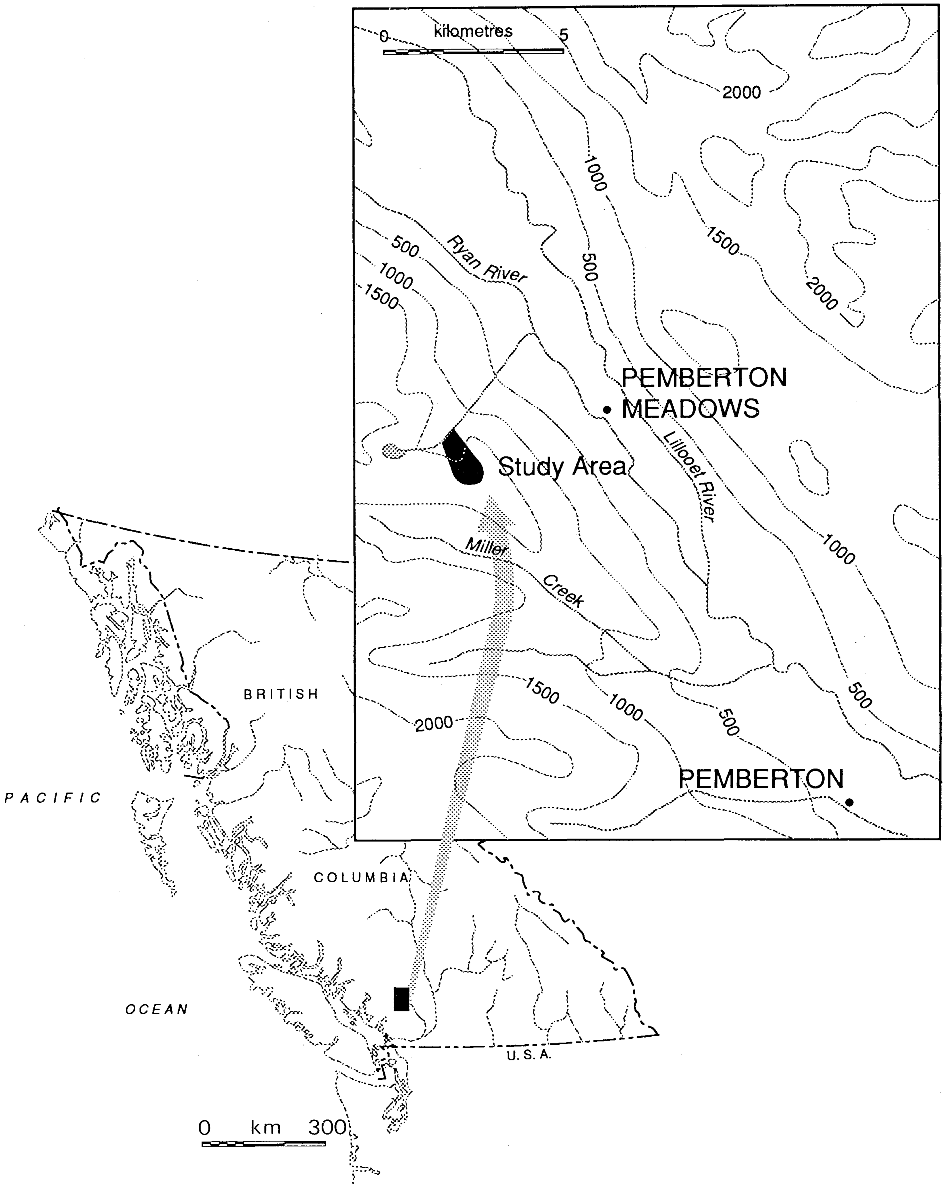

Fig. 2 The location of the study area in British Columbia.

0.005 to 0.220 t km^{-2} year^{-1}. These values show an increase in sediment yield with a decrease in elevation. The Gallie Pond catchment is above the timberline and has the lowest sediment yield, while Ash Lake catchment is below the timberline and has a sediment yield two orders of magnitude greater. Middle Lake, which lies approximately midway between the two, has a yield that is intermediate in magnitude. This situation is the converse of conventional wisdom, which has assumed that, because of the incomplete vegetation cover, the high precipitation intensity and the high energy environment of the alpine

Table 1 Morphometric characteristics of the study lakes in the summer of 1989.

	Gallie Pond	Middle Lake	Ash Lake
Altitude (m a.s.l.)	1850	1710	1624
Surface area (m^2)	901	600	618
Maximum length (m)	54	35	43
Maximum width (m)	21	28	22
Max. water depth (m)	1.23	0.48	0.55
Water volume (m^3)	505	96	142
Catchment area (km^2)	0.023	0.202	0.022
Catchment: lake ratio	26:1	337:1	36:1

zone, sediment yields in unglacierized alpine catchments should be relatively high (e.g. Fournier, 1960; Büdel, 1968; Young, 1974). According to these workers, the lack of vegetation above the timberline is likely to promote an increase in soil detachment and transportation by direct raindrop impact and increases the likelihood of overland flow by reducing infiltration and soil binding. Furthermore, areas of bedrock and surficial material are exposed directly to atmospheric weathering. An inverse relation between specific sediment yield and elevation has also been suggested for the Colorado Front Range, where studies have shown that above the timberline material is essentially contained within the catchments, while below, sediment yields are higher as a result of larger-scale fluvial and colluvial processes (Bovis, 1978).

Table 2 Clastic sediment yields for the three catchments based on lake sedimentation over the last 2350 years (yields have been corrected for non-catchment derived material and for outflow losses).

Catchment	Area (km^2)	Altitudinal range (m)	Clastic sediment yield ($t\ km^{-2}\ year^{-1}$)
Ash Lake	0.022	1624-1850	0.220
Middle Lake	0.202	1710-1970	0.030[a]
Gallie Pond	0.023	1850-1900	0.005

[a]This is probably an underestimate of the true value (Owens & Slaymaker, 1992).

Field measurement of the operation of individual contemporary geomorphic processes in the Gallie Pond catchment (Jones, 1982), when integrated over the whole catchment, account for significantly more sediment flux (0.3 to 1.2 $t\ km^{-2}\ year^{-1}$) than the lake sediment-based sediment yield (0.005 $t\ km^{-2}\ year^{-1}$) (see also Souch & Slaymaker, 1986). This catchment appears to have a stream subsystem that is decoupled from the hillslope subsystem, with material eroded from the hillslopes going into storage. Such a phenomenon has also been suggested for catchments above the timberline in the Colorado Front Range (Bovis & Thorn, 1981; Caine & Swanson, 1989), the central Pyrenees in Spain (Diez *et al.*, 1988) and the Polish Tatra Mountains (Kotarba *et al.*, 1987). In the Middle and Ash lake catchments, which have steeper slopes and a greater relative relief (260 m and 226 m, respectively, compared to *c.* 50 m for the Gallie Pond catchment), the fluvial and hillslope subsystems may become periodically linked by episodic large scale mass movements such as debris flows and rock avalanches (Jordan & Slaymaker, 1991).

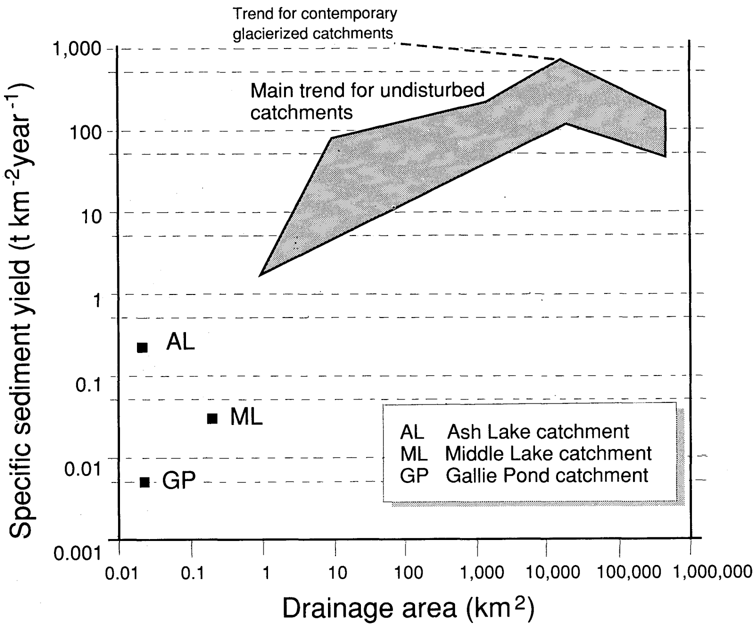

Fig. 3 Specific sediment yield as a function of drainage area for fluvial suspended-sediment records in British Columbian rivers (adapted from Church & Slaymaker, 1989) and lake sediment-based yields in alpine and subalpine catchments (this study).

The sediment yields for the three catchments studied are orders of magnitude lower than the regional rates for larger catchments (Fig. 3). This result is not inconsistent with the hypothesis for British Columbia of scale controls on clastic sediment yield. Figure 3 illustrates specific sediment yield as a function of catchment area for British Columbian rivers and for the catchments examined in this paper. The main trend for undisturbed catchments has a local range of between one-half and one order of magnitude in yield. This is probably due to variable Quaternary and bedrock geology (Church & Slaymaker, 1989). The trend for glacial rivers superficially conforms to the conventional model. However, most of the sediment yield is derived from the glacial headwaters, and the apparent decline in specific sediment yield downstream may be mainly a consequence of the increase in nonglacierized catchment area (Church *et al.*, 1989). In the larger catchments, the major sources of sediment are Quaternary deposits stored along the river banks and immediate valley walls. Consequently, contemporary sediment yields in these catchments are more a result of processes that operated in the Quaternary than of contemporary denudation of the land surface. Specific sediment yield decreases with increasing area for catchments greater than *c.* 3×10^4 km^2 in size as the rivers in these catchments generally flow in relatively wide valleys with flood plains or have developed major sediment accumulations along the channels. These features sometimes protect non-alluvial banks from fluvial attack, so that the recruitment of sediment becomes less continuous and less intensive (Church *et al.*, 1989).

CONCLUSION

Sediment yields for the three small alpine-subalpine catchments range from 0.005 to 0.220 t km^{-2} $year^{-1}$ and show an increase in yield with a decrease in elevation. In the catchment above the timberline a large proportion of the material eroded from the hillslopes goes into storage, while for the catchments below the timberline the hillslope and fluvial subsystems are better linked. When placed in a regional context, sediment yields are low and support a hypothesis for British Columbia of scale controls on sediment yield. In larger catchments sediment is being reworked from storage zones along river banks and valley walls.

Over long time periods (10^5 years or longer) specific sediment yield may accurately reflect erosion and primary denudation rates. Here primary denudation is defined as the progressive exposure of deeper rock structures by weathering and erosion (Fairbridge, 1968). However, at time scales of 10^0 to 10^4 years, this may not be the case and sediment yields in glaciated and glacierized terrain are dominated by storage effects. Contemporary sediment (and possibly solute) yields and transfers probably consist of two components:
(a) primary denudation of bedrock;
(b) gain or loss of sediment (and solutes) due to storage effects.
Consequently, in British Columbia, and other similar environments, specific sediment yield may not equate with primary denudation of the land surface at any spatial scale, though it will tend asymptotically towards that value as catchment size decreases.

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