Available online at www.sciencedirect.com
ScienceDirect
ELSEVIER
Geomorphology 79 (2006) 27 – 44
GEOMORPHOLOGY
www.elsevier.com/locate/geomorph

The use of sediment budget concepts to assess the impact on watersheds of forestry operations in the southern interior of British Columbia

Peter Jordan *

British Columbia Ministry of Forests, Kootenay Lake Forestry Centre, 1907 Ridgewood Rd., Nelson, BC, Canada V1L 6K1

Accepted 29 September 2005
Available online 20 March 2006

Abstract

Sediment budget concepts can be applied to the assessment of the impacts of forest resource development on the sediment regime of streams. In British Columbia, these impacts are of concern because of the extent of commercially valuable forests. Increases in sediment yield from forestry operations can affect water quality, fish habitat, and channel stability. To address these concerns, the BC Ministry of Forests conducted several sediment budget studies from about 1992 to 2002. This paper reports the results of two studies, focusing on the water quality of streams used for community water supply. The studies address several questions: How sensitive are the streams to an increase in sediment supply? Are development-related sediment sources significant compared to natural sources? What forest practices are responsible for increasing or minimizing sediment impacts? How can the impact of forestry operations on water quality be monitored? The studies used a paired watershed approach, with discharge, turbidity, sediment yield, and solute yield measured on watersheds undergoing logging and road building, and on similar undeveloped watersheds. The studies concluded that erosion from forest roads can be a significant source of suspended sediment, but sediment from logging operations is usually negligible. The risk of landslides is an important factor in the sediment budgets, but is difficult to quantify. Differences in geology and groundwater regime can influence the sensitivity of watersheds to sediment impacts.

Keywords: Sediment budget; Turbidity; Erosion; Forest roads; Forest practices; British Columbia

1. Introduction and objectives

The water quality of streams used for water supply in the southern interior of British Columbia is an important issue. Many water users in rural areas depend on surface water, and use it with little treatment. Most cities and towns in the region obtain their water from mountain streams, although they employ reservoirs and treatment systems. The watersheds supplying these streams are part of the provincial forest, and are used for timber harvesting. Water quantity and quality, the sediment yield of streams, and the effects of timber harvesting and forest roads on these, are important concerns for forest management. Fish habitat and flooding are additional concerns on some streams.

The British Columbia Ministry of Forests has conducted research programmes on sediment budgets, erosion and sedimentation issues related to forest development, and on streamflow and snow hydrology,

* Tel.: +1 250 825 1119; fax: +1 250 825 9657.
E-mail address: peter.jordan@gov.bc.ca.

0169-555X/$ - see front matter © 2006 Elsevier B.V. All rights reserved.
doi:10.1016/j.geomorph.2005.09.019

beginning in the early 1990s. This paper will discuss some results of this research in the Kootenay region of southeastern British Columbia, a region where communities are particularly dependent on surface water, and where forest development in watersheds is often a contentious issue.

The objectives of this paper are:

1. to summarize the past 10 years of watershed research in this region, especially with respect to sediment budget results;
2. to compare sediment and solute budgets in watersheds with different bedrock geology and soil texture, and in different hydrologic environments;
3. to illustrate the practical application of sediment budget concepts to assessing the impacts of forest resource development on streams and water quality.

Some additional objectives of the research programme, which have been discussed in more detail elsewhere (Jordan and Commandeur, 1998; Jordan, 2001), include: to identify natural and development-related sources of sediment; to investigate the effect of road engineering and forest harvesting practices on sediment production; and to collect data on hydrologic events which are significant in sediment production.

2. Sediment budget studies: principles and previous work

A sediment budget study requires quantification of the sources of sediment, changes in sediment storage in the stream channel network, and sediment discharge at the stream outlet. This can be expressed as an equation:

$$I = O + \Delta S$$

where I is input, O is output, and S is change in storage. The equation can be applied at any scale of interest, from an entire watershed to a single reach of stream channel. In practice, the equation is often applied separately to suspended sediment (fine sand, silt, and clay), and bedload (coarse sand and gravel), since the physics of transport and storage of the two types of sediment are different. The theory and methodology of sediment budget studies have been described in the literature (Swanson et al., 1982; Reid and Dunne, 1996). The solute budget of a watershed can be expressed in the same terms, although once dissolved solids reach the stream channel system, storage (except in arid environments) is negligible.

A sediment budget framework for the study of geomorphic processes in forested drainage basins was developed in the Pacific Northwest region of the United States in the 1970s, where it was applied to investigating the response of stream channels to extreme meteorological events and to disturbance from forest development (Dietrich and Dunne, 1978; Swanson et al., 1982). The importance of sediment from forest road erosion was realized at this time, and several studies addressed the role of sediment from forest roads on the sediment budget (Beschta, 1978; Reid and Dunne, 1984; Megahan et al., 1986; Keppeler et al., 2003). In British Columbia in the 1980s, several studies examined the role of glaciation, and in particular, the storage and renewed erosion of Pleistocene glacial deposits, in the sediment regime of rivers. Slaymaker (1987) noted that non-glacial (but previously glaciated) headwater drainage basins in British Columbia tended to have lower sediment yields than mainstem rivers, which is opposite to the pattern observed in other, non-glaciated environments throughout the world, and that in many of these headwater basins, sediment yield is unexpectedly low and is exceeded by solute yield. Church and Slaymaker (1989) presented a model of sediment budgets for glaciated river basins in which sediment yield increases downstream as the large volumes of Pleistocene glacial deposits stored in major river valleys are eroded.

Most sediment budget studies have focused on drainage basins where sediment yields are very high (e.g. Kelsey, 1980; Roberts and Church, 1986; Madej, 1997; Jordan and Slaymaker, 1991). Such drainage basins, which often have highly disturbed channels and hillsides, present many resource management and engineering problems, and therefore have received the most attention. In the mountain and plateau regions of British Columbia, especially in the Interior, much forest resource development takes place in an environment which is geomorphically inactive and in which, at present, sediment yields are very low. The streams draining these areas often have very productive fisheries, and in populated areas are often used as community water sources. Their low sediment yields can make them disproportionately sensitive to geomorphic events resulting from development, such as soil erosion and landslides, since these events can result in a relatively large change to the sediment budget, and significant impacts to downstream resources.

Church et al. (1989) reviewed data on suspended sediment yield from streams in western Canada, derived from sediment sampling programs of the Water Survey of Canada, BC Hydro, and other agencies. The data showed that most non-lake-controlled streams had yields ranging from about 10 to 400 T/km^2/year, and show a strong tendency to increasing yield with increasing drainage basin size. In their data set, four streams stand out as having the lowest average sediment yields, about 3 to 8 T/km^2/year. These are four community watersheds in the West Kootenay region; all are small (9 to 80 km^2), forested, mountain watersheds. This data set illustrates the point discussed below, that low sediment yield is a factor in choosing surface water sources for community water supply.

In British Columbia in the early 1990s, the Ministry of Forests established a program of multi-year research projects using a sediment budget approach to study the impacts of forest resource development on streams. One of the objectives of these studies was to provide a scientific basis for a watershed assessment procedure, to describe and predict the effects of past and future forest roads and harvesting on stream channels, streamflow, and sediment yield (Toews and Henderson, 2001). Sediment budget studies were set up in four areas of the province: the Tsitika River watershed on northern Vancouver Island (Hudson, 2001), the Stuart-Takla watersheds in the northern Interior (Macdonald et al., 2003), the Penticton Creek watershed in the Okanagan region (Winkler et al., 2003), and at two sites in the Kootenay region (this study). The first two of these projects addressed fish habitat concerns, while the others addressed water quality in community and domestic watersheds.

3. The study area, study design, and history of the project

The work described here was conducted in the Kootenay region of southeastern British Columbia, which comprises approximately the drainages of Kootenay River, and Columbia River from Arrow Lakes downstream to the U.S.A. border (Fig. 1). The region is mountainous, and includes the southern parts of the Rocky Mountains and Columbia Mountains, along with several intermontane valleys (Holland, 1964). Valley bottom elevations range from 430 to 900 m, and the mountain ranges have peak elevations of about 2400 to 3300 m.

The region is divided, by geology and climate, into west and east halves (Jungen, 1980; Ryder, 1981). The West Kootenays are underlain mainly by granitic rocks, gneiss and schist of various ages, and Mesozoic sedimentary and volcanic rocks. In the East Kootenays, the geology is mainly Precambrian and Paleozoic sedimentary rocks. The region was glaciated during the Pleistocene epoch, and most soils are derived from till and other glacial deposits, which are typically thin (2 m or shallower) at high elevations and on ridge tops, and

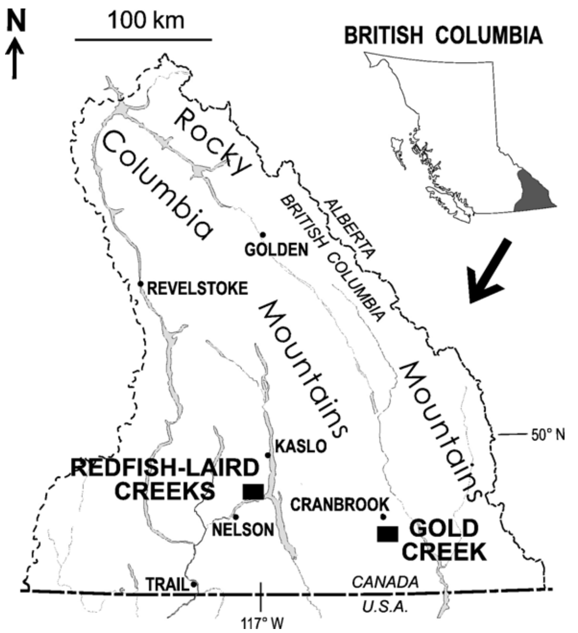

Fig. 1. Map showing location of the study watersheds, Redfish Creek, Laird Creek, and Gold Creek, in southeastern British Columbia. The area outlined is the Nelson Forest Region.

much thicker in the valley bottoms. Precipitation in the valleys ranges from 800 mm in the west to 450 mm in the east, with local anomalies in some mountain valleys. Above about 1200 m elevation, most precipitation falls as snow. Most of the West Kootenays is part of an interior rain forest, and is dominated by dense cedar and hemlock forests. The East Kootenays are generally drier, with spruce, Douglas fir, and pine forests more abundant. Forestry is an important economic activity throughout the region.

Population in the region is mainly confined to the valley bottoms. There are several cities, including Cranbrook and Nelson, but much of the population lives in small towns, villages, and rural areas dispersed throughout the valleys. When permanent settlements were established in the region, about 100 years ago, most residents used local creeks as water sources because they provided water that was abundant, free, and of high quality. In populated valleys throughout the region, but particularly in the West Kootenays, most creeks have domestic (single-user) or community water licenses, and most towns and cities rely on surface water sources. In about the last 30 years, industrial-scale forest development has been taking place in many of these watersheds, leading many water users to perceive that this development is a threat to their water quality. Opposition from domestic water licensees has become a major constraint to the planning of forest development.

An important aspect of the surface water resource in the region is that most community and domestic watersheds are forested and of moderate relief, with a very low level of geomorphic activity and hence low suspended sediment concentration. These watersheds were selected as water sources for precisely this reason; the low sediment yield means that the water is normally of very high quality. There are many watersheds in the region which are more geomorphically active, with glaciers or landslide features and relatively high sediment yields; however, these streams have not been chosen as water sources.

Two long-term sediment budget and streamflow monitoring studies have been established by the Ministry of Forests in the region. The first of these, Redfish and Laird Creeks, is in the West Kootenays near Nelson. This study was established in 1992, on a paired watershed principle (Jordan, 2002a). The two creeks supply a total of 84 water licenses, and are typical of the many domestic watersheds in the area. Near its mouth, Redfish Creek is also important as habitat for spawning Kokanee salmon. The second study began in 1998, and is located in the Gold Creek watershed in the East Kootenays, one of two community watersheds supplying the city of Cranbrook (Jordan, 2002b). The general location of these study areas is shown in Fig. 1. The last year of sediment budget results is 2002 for Redfish/Laird Creeks, and 2003 for Gold Creek. Table 1 provides some summary data for the two study areas.

Redfish and Laird Creeks are adjacent watersheds which are of similar size, and have similar landforms and hydrologic characteristics. They are underlain by granite, with thin, sandy soils in most areas. The watersheds are mountainous; roughly 10% of the area is alpine and 50% is operable forest, with the remainder being forested land which is too steep or too inaccessible for forestry operations. There are several small lakes near the headwaters, however most of the watershed area is not lake-controlled, and the streams have steep, boulder-dominated channels which respond quickly to hydrologic events. Redfish Creek has a long history of forest harvesting, which is continuing, while Laird Creek is undeveloped. Fig. 2 is an air-photo based map of the two watersheds.

In addition to hydrometric and sediment sampling stations near the mouths of the two creeks, there is a network of climate stations and snow courses in the Redfish Creek watershed. A tributary of Redfish Creek was selected for more detailed study, with two measurement stations located upstream and downstream of development. Thus there are two developed/undeveloped pairs in the project: the adjacent watersheds of Redfish and Laird Creeks, and the Redfish Creek tributary at a smaller scale, with an upstream–downstream pair.

The main objective of the sediment budget study in the Cranbrook City watershed was to study a different hydrologic and geologic environment from those in

Table 1
Watershed characteristics

	Redfish/Laird Creeks				Gold Creek			
Mean annual precipitation at representative climate station[a]	828 mm (Kaslo, 588 m)				451 mm (Cranbrook, 918 m)			
Mean late winter snow water equivalent at representative snow course[b]	1393 mm (Redfish Cr, 2104 m, May 1)				401 mm (Moyie Mtn., 1930 m, April 1)			
Geology	Nelson batholith (Jurassic) granite				Purcell group (Precambrian) argillite, siltstone, shale, dolomite, basalt			
Watershed[c]	Redfish Cr	Laird Cr	RU1	RU2	Gold Cr	GA	GB	GC
Drainage area (km^2)	26.2	15.0	1.15	0.68	95	2.55	3.38	2.73
Elevation range (m)	700–2370	810–2360	1330–2168	1690–2168	1300–2160	1500–2030	1500–2140	1550–2140
Roads (km)	19	0	2.0	0	n/a	5.2	0.8	0
Logged area (km^2)	2.6	<0.1	0.19	0	n/a	0.68	0.23	0

[a] Valley-bottom climate stations in nearby towns; locations are shown in Fig. 1.
[b] Snow courses at ridge-top elevation in or near the watershed.
[c] Areas for Redfish, Laird, and Gold Creeks are measured at gauging stations near the mouth of each drainage. RU1 and RU2 are two stations on a tributary of Redfish Creek (Fig. 2). GA, GB, and GC are tributaries of Gold Creek (Fig. 3).

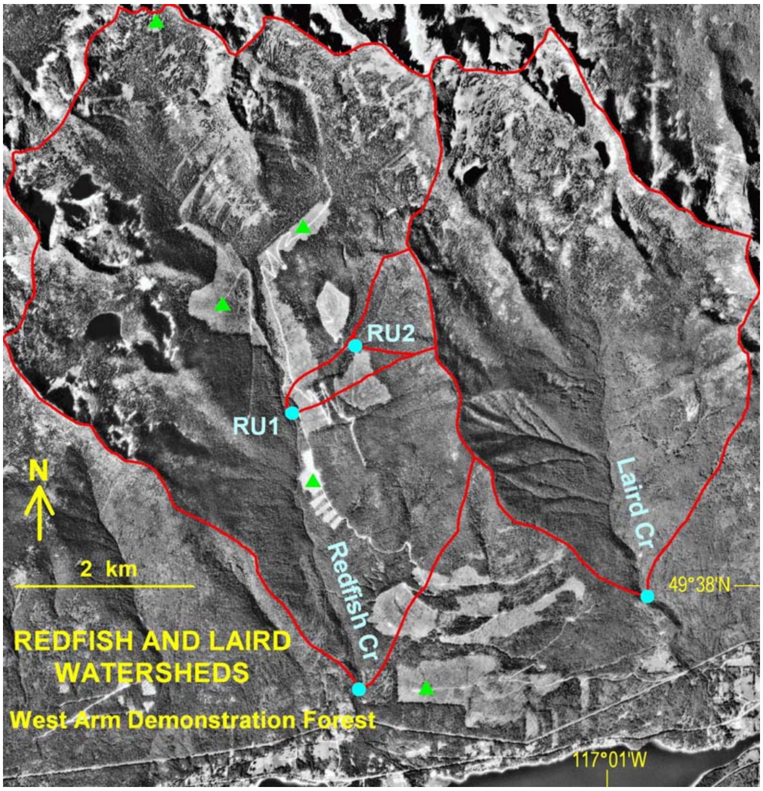

Fig. 2. Map of Redfish Creek and Laird Creek watersheds, based on an orthophoto. Round dots are streamflow and sediment monitoring stations. RU1 and RU2 are the lower and upper stations, respectively, in the Redfish Upper tributary. Triangles are climate stations.

which past studies have been conducted. The drier and colder climate of the East Kootenays, and the sedimentary bedrock geology, are quite different from those of the West Kootenays and the Okanagan, where other studies in the southern interior of British Columbia have been located. The project is located in the watershed of Gold Creek, with a year-round streamflow station situated a short distance upstream from the city's water diversion pipeline. Fig. 3 is a map of the watershed based on a satellite image. The watershed is less mountainous than Redfish and Laird Creeks, consisting of hilly terrain which is almost entirely covered with operable forest. Soils are dominantly silty, and are derived from thin, stony till in upland areas, and deep, sometimes fine-textured, glacial deposits in the main Gold Creek valley. For detailed study, three small headwater tributaries of Gold Creek were selected, one of which had extensive development planned for 1998–1999, one with a lesser amount of past development, and one which is undeveloped. These are called GA, GB, and GC respectively, and are shown in Fig. 3. Summary data on the watersheds are given in Table 1.

4. Methodology

The methods used to measure components of the sediment budget are briefly described here. Some further detail on the field installations is given in Jordan and Commandeur (1998). This study focuses on suspended sediment. Since in the high-energy stream systems of this study, storage of suspended sediment is negligible, the results are not expressed in terms of the sediment budget equation; instead, the emphasis is on reconciling the inputs (sources) and outputs of suspended sediment. An attempt has been made to estimate the inputs of coarse sediment, but measurements of bedload discharge were beyond the scope of this study, and a budget for streambed sediment has not been computed.

4.1. Stream discharge

Streamflow on Redfish and Laird Creeks was measured year-round at Water Survey of Canada (WSC) recording stations. Redfish Creek is a permanent station with 32 years of record. The Laird Creek station was installed in 1993, and was discontinued in 2000; seasonal

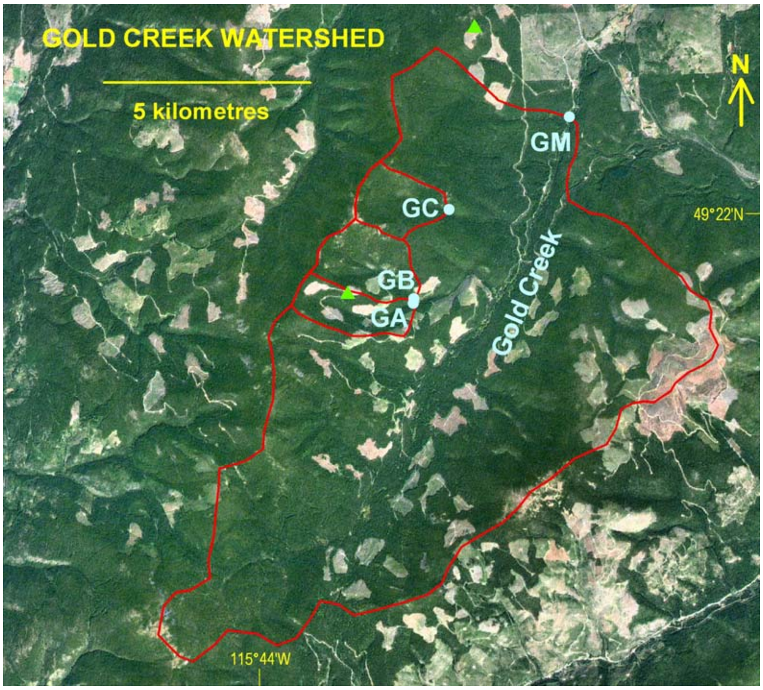

Fig. 3. Map of Gold Creek watershed, based on a satellite image. Round dots and labels indicate the four streamflow and sediment monitoring stations. GM is the site of the hydrometric station on Gold Creek; GA, GB, and GC are the detailed study tributaries. Triangles are climate stations.

(April–October) data collection continued until 2003. On the upper tributary of Redfish Creek, two V-notch weirs were installed in 1993, one near the mouth of the stream, and one at a point above the roads and logged area. This stream is referred to as "Redfish Upper", and the two sites are labeled RU1 and RU2 in Fig. 2. At each site, water level was recorded during the spring to fall season (April–October). The theoretical rating curve for each weir was checked, and modified for high flow, with discharge measurements made by salt dilution gauging.

On Gold Creek, a year-round gauging station was installed in late 2001 (site GM in Fig. 3). From 1999 to 2001, water level was measured seasonally, and an approximate rating curve was established by flow metering. Seasonal (April–October) stations were installed on the three tributaries in 1998, using rectangular weirs at two sites, supplemented by flow metering at high flows. On the third tributary (GC), which is at a remote site, a rating curve was maintained with frequent flow metering.

At all stations, water level was measured with pressure transducers to a precision of about 1 mm, and data were recorded with a temporal resolution of 15 min.

4.2. Turbidity and suspended sediment concentration

At all of the streamflow measurement sites, continuously recording turbidity meters (optical back-scatter, or OBS meters) were installed, for the April–October season.

Water samples were collected manually near the mouths of Redfish and Laird Creeks from 1993 to 1999, daily during the spring freshet and weekly at other times in the April–October season. Beginning in 2000, automatic pump samplers were used to collect samples at the Redfish and Laird Creek gauging stations. At Gold Creek, pump samplers were installed in 1998 at the three tributary sites, and in 2001 at the GM gauging station. On Redfish and Laird Creeks, streamflow and turbidity show a strong diurnal variation during the snowmelt season. All daily samples were taken in late afternoon, close to the time of peak discharge and turbidity. The turbidity of each sample was measured in the lab, and samples which exceeded a threshold turbidity of 1 NTU were analyzed for suspended sediment concentration.

The results of the sampling enabled a regression relationship to be established between turbidity and suspended sediment concentration for each creek. Theoretically, the continuous recording of turbidity can be used to derive a continuous suspended sediment discharge hydrograph (Jordan and Commandeur, 1998). However, the turbidity meters were found to frequently give misleading results, and it was difficult to interpret the data (Jordan, 1996). False readings due to obstruction by debris, air bubbles, and moving bedload are common, especially at high flows. For instance, when installed in a fast-flowing stream the OBS meter often gave a much higher reading than samples collected at the same time and measured in the lab. The disagreement was greatest at high flows, and in steep, highly turbulent streams. In less turbulent water, including the ponds behind weirs, the OBS meters gave more reliable results. Because of the problems with the OBS meter data, they were not normally used to calculate suspended sediment concentration and sediment yield, but were used mainly for the purpose of qualitatively interpreting individual sediment yield events. When necessary, and only when the data were believed to be reasonably reliable, the OBS meter data were used to estimate suspended sediment concentration for times when samples were missing.

4.3. Suspended sediment yield

The daily suspended sediment yield was calculated as the product of mean daily discharge and a suspended sediment concentration which was assumed to be representative for the day. If more than one sample was taken on a particular day, the concentrations were averaged. The annual yield was calculated as the sum of the daily yields for the season from April to October. This is actually a seasonal yield; however, with one rare exception as noted below, streamflow in this region from November to March was always very low, and sediment concentration was below detectable levels, so the seasonal yield closely approximates the annual yield (Church et al., 1989).

For days when suspended sediment concentration data were missing, a regression relation between sample turbidity and concentration was used. This relation was calculated for each station and each year; an example of one relation is shown in Fig. 4. Usually, this relation was used to estimate concentration only for days when turbidity was below 1 NTU.

Inevitably, samples were missed on some days. Also, during low flow seasons, samples were only collected every several days. To estimate the missing data, relations were plotted between suspended sediment and discharge. An example of such a relation is shown in Fig. 5. These relations typically show a large amount of scatter and strong seasonal hysteresis. To estimate the sediment yield on missing days, lines were drawn by eye through the early-season and late-season clusters of points. The scatter in these relations is a major source of error in the calculated sediment yields, for stations and years with missing data at high flows.

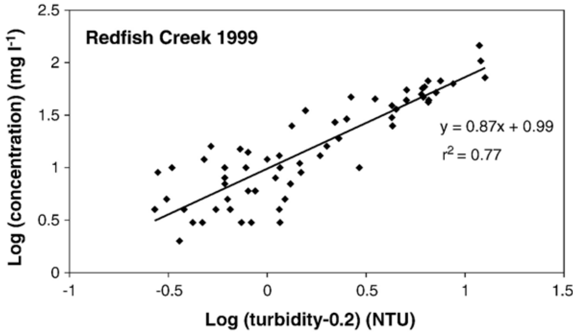

Fig. 4. Example of a turbidity–concentration curve. Horizontal axis (x) is log of turbidity minus 0.2 NTU; this is used because turbidity converges on a value of 0.2 NTU when suspended sediment concentration is zero. Vertical axis (y) is log of suspended sediment concentration.

The assumption that one suspended sediment sample per day is representative is a source of error, as concentration varies both randomly and systematically throughout the day. Because samples were normally collected in the afternoon, during the daily maximum of flow and turbidity during snowmelt events, the calculated daily sediment yield is positively biased. From the limited data available for days with multiple samples, this bias may be approximately 25–50%, and it applies only to days when snowmelt (rather than rainfall) is the dominant process.

4.4. Bedload

Bedload discharge is difficult to measure on all but the smallest streams, and for the main-stem creeks, bedload measurements were beyond the resources of this study. On small streams such as the Redfish Upper and Gold Creek tributary sites, weirs serve as total retention traps, and enable bedload discharge to be measured at these sites. Other than miscellaneous observations of channel storage and bedload material, we have not attempted to quantify the bedload component of the sediment budget for the main channels. For the purpose of this paper, bedload yield measurements on the small tributaries have been extrapolated to attempt an order-of-magnitude estimate of possible bedload inputs for the entire watershed.

4.5. Solutes

Throughout the study, conductivity and total dissolved solids concentration (TDS) were measured on a sporadic basis. Beginning in 2002, the conductivity of all water samples was recorded, and TDS was measured on sufficient samples to derive conductivity–TDS

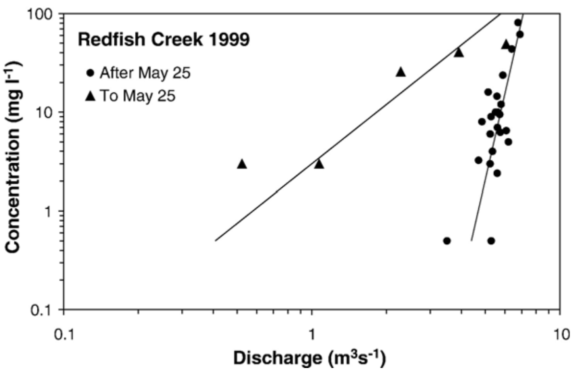

Fig. 5. Example of a discharge–concentration curve, used to estimate suspended sediment concentration for days when no water sample was taken. Left cluster of points (triangles) is early season samples (to May 25 in this example); right cluster (dots) is the remainder of the spring runoff period. The lines are fit by eye.

relations and calculate annual solute yield. The purpose of these measurements was to help interpret runoff generation mechanisms in the watersheds, in particular the partitioning of snowmelt runoff into surface and near subsurface flow, and groundwater flow.

4.6. Sediment source inventories

An important part of this study was to estimate the input of sediment to the stream channels from various sources, especially those related to forest development, and attempt to reconcile sediment inputs and outputs in the watersheds. In these geomorphically inactive watersheds, there was a scarcity of site-specific sediment sources such as landslides. During field work, it became apparent that most natural sediment inputs were from diffuse sources such as small-scale bank erosion along ephemeral tributaries, soil from uprooted trees bordering streams, organic material derived from leaf drop along channels, and rarely, small debris flows in steep headwater tributaries. These sources are difficult to quantify. Instead of attempting to measure all sediment inputs, an estimate was made of the background, or natural, suspended sediment sources from the sediment yield of the undeveloped watersheds, and this was compared to estimates of sediment originating from forest roads and cutblocks.

These development-related sediment sources were inventoried with a variety of methods, including weirs on ephemeral water courses, sediment traps on logged areas and below road culverts, and annual surveys of erosion along roads. These are described in Jordan and Commandeur (1998). As the study progressed, the data from these surveys showed that erosion from roads was by far the most important development-related sediment source. Beginning in 1997, systematic surveys of road erosion were made following the spring snowmelt season (when most erosion typically occurs), and sporadically on other occasions following severe rainstorm events. The procedure used for these surveys is described in Henderson et al. (1999) and in Toews and Henderson (2001). In brief, measurements and estimates were made of sediment removed from rills in road surfaces, ditches, and cutbanks. Estimates were made of the proportion of eroded sediment which is transported from the road to the stream channel network by observing sediment trails below roads, and by comparing the soil texture of the source material with that of deposition sites.

5. Results and discussion

The following sections give a brief discussion of the general results of the studies, concentrating on estimates of the annual sediment and solute yields, and on aspects of the results which focus on geomorphic and hydrologic processes controlling the sediment and solute budgets. Further details on the results of each year, and data compilations, can be found in Jordan and Commandeur (1998), Jordan (2002a), and Jordan (2002b).

5.1. Runoff, turbidity, and hysteresis

Some useful information on the runoff and sediment regime can be obtained by examining the records from some of the gauging sites for typical years. Fig. 6 shows mean daily discharge for Redfish Creek, and sample turbidity for both Redfish and Laird Creeks, for 1997. Most of the runoff and sediment yield for the year occur during the snowmelt period, from May through July. The highest peak for this example (in mid-June) is caused by a rain-on-snow event; such events are often the peak discharge and sediment-producing event of the year. The other major peaks are radiation-driven snowmelt events. Fall rainstorms cause lesser hydrograph peaks and sediment yield events. The water sample data typically show the highest turbidity on the first few hydrograph peaks, with declining turbidity during the main snowmelt runoff peak. This seasonal hysteresis occurs because with the first rise of water level in the spring, sediment and organic debris which has accumulated along the channel margins during the previous summer and fall, and in other storage sites such road ditches and ephemeral water courses, are washed into the creek.

Fig. 7 shows a more detailed record of water level and turbidity (as measured by the OBS meters) for a

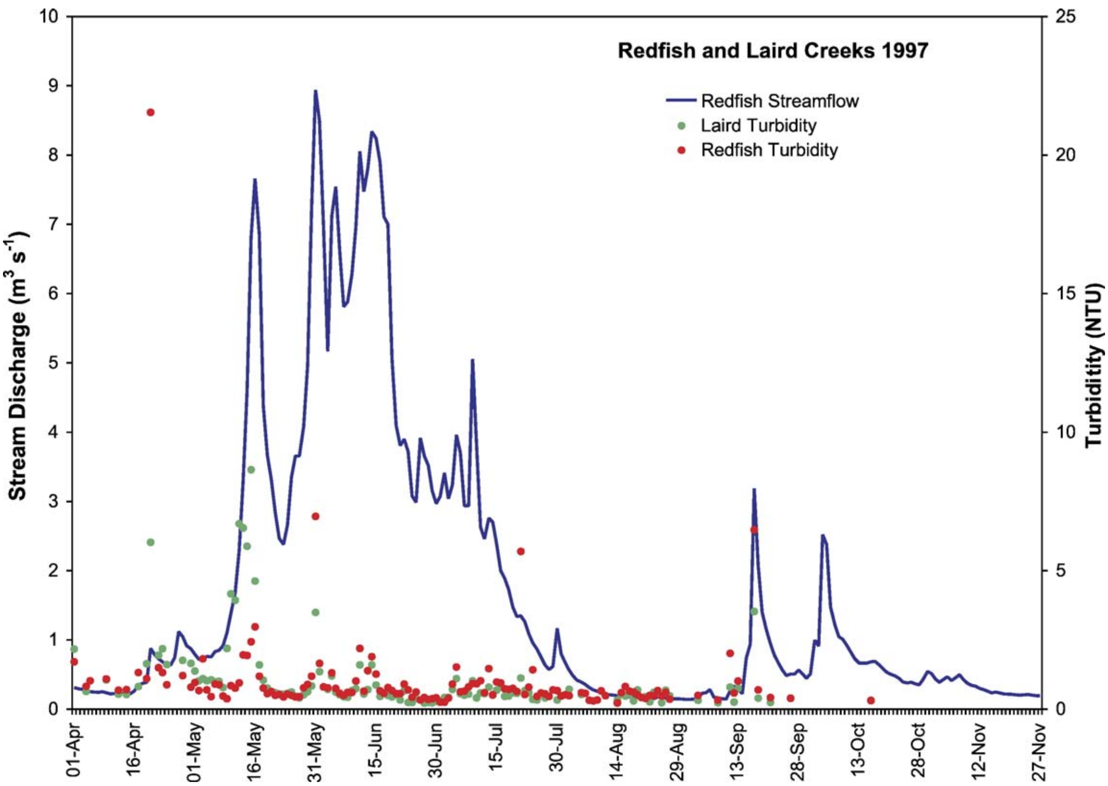

Fig. 6. Example of a hydrograph of mean daily discharge for Redfish Creek for one season, and turbidity samples for Redfish and Laird Creeks.

typical season at the two sites on the Redfish Upper tributary. From these graphs, it is evident that turbidity is consistently higher at the lower site; this difference is probably due to erosion from roads between the two sites. Also apparent is the strong diurnal variation in water level and turbidity; the two major peaks are during clear warm weather, with radiation-driven snowmelt.

Fig. 8 shows comparable data for the same time period, for two of the Gold Creek sites, the tributary which had recent logging and road construction in its watershed (GA) and the undeveloped tributary (GC). Although a small peak in turbidity is apparent on the first hydrograph rise for GA, generally the difference in turbidity between the developed and undeveloped drainages is less for Gold Creek than for Redfish Creek. Another difference is that the Gold Creek hydrographs lack the diurnal variability that is prominent at Redfish Creek. Both observations may be attributable to differences in the relative importance of surface runoff and groundwater (Jordan, 2001), as discussed further below.

Fig. 9 shows plots of turbidity against water level for the Redfish Upper tributary (site RU1) for the same representative snowmelt period, demonstrating hysteresis at both daily and seasonal time scales. At a given water level (hence discharge), turbidity is higher on the rising limb than on the falling limb of the hydrograph. The reasons for hysteresis at the daily scale are less obvious than for the seasonal scale; however, daily hysteresis was consistently observed at all sites where there was strong diurnal streamflow fluctuation during snowmelt. A probable explanation is deposition of fine sediment in pools and along the channel margins during low flow, followed by entrainment during rising flow the following day. Another process which contributes to hysteresis during snowmelt is small-scale erosion on roads, in ditches, and along small ephemeral water courses, as the snowline rises and new erosion sites are exposed each day.

5.2. Suspended sediment yield

The annual suspended sediment yield and runoff data for the studies are summarized in Table 2 (Redfish and Laird Creeks) and Table 3 (Gold Creek). The sediment yield results are generally in the range reported by Church et al. (1989) for community watersheds in the Kootenay region; that is, amongst the lowest yields in British Columbia. At Gold Creek, the yields are

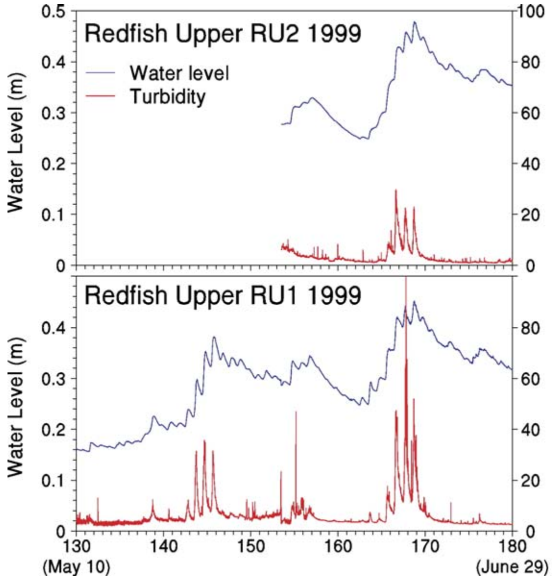

Fig. 7. Water level and turbidity for two sites on the Redfish Upper tributary for the snowmelt season of 1999. Horizontal axis gives the day of the year. The turbidity graph is output from the OBS meter, uncorrected for false signals or drift of the instrument zero. Water level is measured to the lowest point of the weir edge. Data are recorded at 15-min intervals. Top: upper site (RU2). Bottom: lower site (RU1).

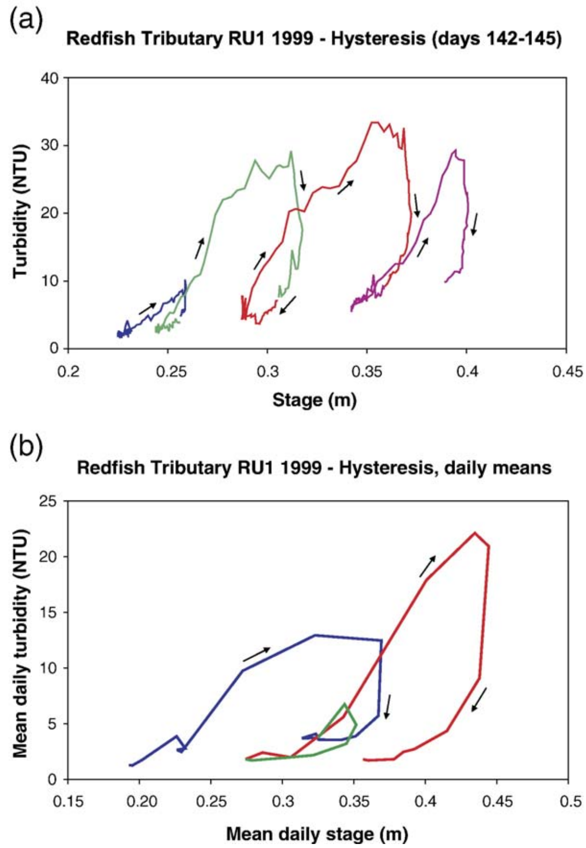

Fig. 9. Graphs showing hysteresis of turbidity. The data are from the turbidity and water level record shown in Fig. 7. (a) Four days of record (days 142–145) during a peak snowmelt period; data points are every 15 min. (b) Daily mean turbidity and water level for a 4-week period which includes most of the seasonal snowmelt runoff.

somewhat lower than at Redfish/Laird Creeks, although the shorter period of record prevents making conclusions about long-term trends.

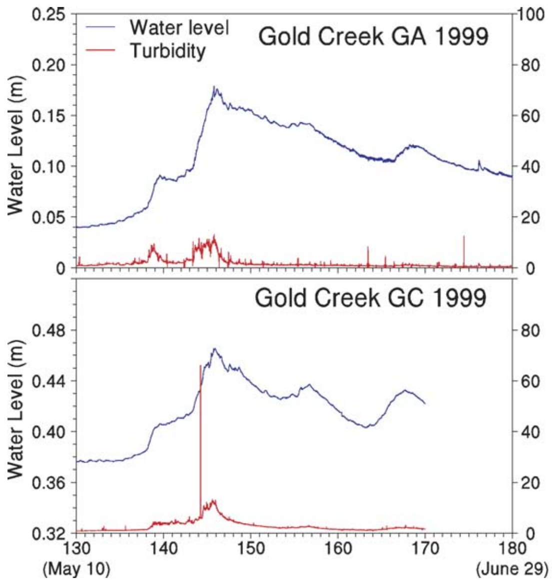

Fig. 8. Water level and turbidity for two tributaries of Gold Creek. Time period and measurements are the same as for Fig. 7. Water level for GC is measured to an arbitrary datum. Top: GA, with recent logging and road construction. Bottom: GC, the undeveloped tributary.

At Gold Creek, there appears to be a trend to a greater sediment yield for the main Gold Creek watershed than for its upland tributaries (although the shorter period of record on the larger stream makes this observation tentative). The main valley of Gold Creek contains extensive glacial deposits; this trend appears to support the Church and Slaymaker (1989) model of increasing sediment yield downstream in glaciated environments. In the smaller and steeper Redfish and Laird Creek watersheds, there are relatively few glacial sediment sources in the narrow lower valleys.

The annual sediment yield totals for Redfish and Laird Creeks are plotted in Fig. 10, along with April–September runoff. There is an obvious correlation between runoff and sediment yield. More importantly, until 2000 Redfish Creek has consistently higher sediment yields than Laird Creek; sediment source surveys have shown that this difference is largely attributable to erosion from forest roads (Jordan and Commandeur, 1998; Jordan, 2001).

Table 2
Summary of suspended sediment yield results for Redfish and Laird Creeks, 1993–2002

Year	1993	1994	1995	1996	1997	1998	1999	2000	2001[c]	2002[c]
Redfish Creek:[a]										
April–Sept. runoff (mm)	600	695	703	1075	1250	820	1297	976	391	1094
Maximum daily discharge ($m^3\ s^{-1}$)	5.28	4.79	5.45	6.51	8.94	6.59	6.89	5.44	5.65	7.42
Redfish Creek:										
April–Sept. total yield (T)[b]	246	58	131	249	299	146	272	100	29	253
April–Sept. yield (T/km^2)	9.4	2.2	5.0	9.5	11.4	5.6	10.4	3.8	1.1	9.7
No. of daily samples > 5 NTU	6	0	5	1	5	3	4	1	1	0
Laird Creek:										
April–Sept. total yield (T)	61	20	55	119	68	44	107	58	42	[d]
April–Sept. yield (T/km^2)	4.1	1.3	3.7	7.9	4.6	2.9	7.1	3.9	2.8	–
No. of daily samples > 5 NTU	4	0	2	2	3	1	2	0	2	8

[a] Discharge and runoff for Redfish Creek are from published or preliminary Water Survey of Canada data.
[b] Sediment yield is calculated from daily samples. For 1993–1995 it was calculated by a different method, and may be slightly underestimated.
[c] 2001 and 2002 data are preliminary; final WSC discharge data have not been received at the time of computation.
[d] Laird Creed sediment yield for 2002 has not been calculated due to missing data. Suspended sediment yield is estimated to be in the range of 10 to 50 T/km^2.

In November, 1999, an unusual rainstorm occurred, which caused the peak instantaneous discharge for the year on Redfish Creek and several other gauged streams in the Kootenay region. This event was probably unique; major fall rainstorms (100 mm or greater) are very rare, and on several gauged streams in the region, it was the highest fall flood on record by a wide margin (Boyer and Jordan, 2001). The sediment monitoring instruments had been removed from the stations for the winter before the event occurred; therefore the sediment yields for 1999 do not include this event, and its sediment contribution is entirely unknown. Road erosion surveys made the following summer did not show an unusual amount of road erosion, and it was not possible to distinguish between erosion that occurred in the fall of 1999 and the spring of 2000. During this event, a small landslide and debris flow occurred in a remote part of the Laird Creek watershed. The entire channel of Laird Creek was destabilized by the debris flow, and a large amount of bedload was mobilized along the channel. Because of this disturbance, beginning in 2000 the suspended sediment yield of

Table 3
Summary of suspended sediment yield results for Gold Creek, 1999–2003

Year	1999	2000	2001	2002	2003
Gold Creek at GM:					
April–Sept. runoff (mm)	250[a]	190[a]	80[a]	294	169
Maximum daily discharge ($m^3\ s^{-1}$)				13.1	4.83
Gold Creek at GM:					
April–Sept. total yield (T)				541	112
April–Sept. yield (T/km^2)				5.7	1.2
No. of daily samples > 5 NTU				20	8
GA:					
April–Sept. total yield (T)	2.8	3.9	0.7	5.4	1.7
April–Sept. yield (T/km^2)	1.1	1.5	0.3	2.1	0.7
No. of daily samples > 5 NTU	1	4	3	11	4
GB:					
April–Sept. total yield (T)	12.5	5.2	0.3	126[b]	3.2
April–Sept. yield (T/km^2)	3.7	1.6	0.1	37[b]	0.9
No. of daily samples > 5 NTU	2	0	0	11	5
GC:					
April–Sept. total yield (T)	1.5	0.7	0.04	5.1	0.7
April–Sept. yield (T/km^2)	0.6	0.2	0.01	1.9	0.3
No. of daily samples > 5 NTU	0	0	0	0	0

[a] Discharge was estimated at high flow; runoff is approximate.
[b] Sediment yield for GB in 2002 is an overestimate, due to bedload entrainment in the water samples.

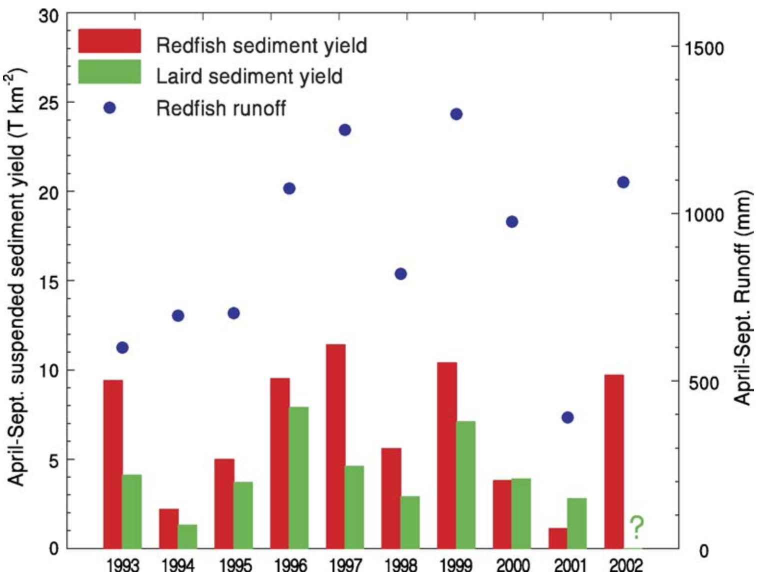

Fig. 10. April–September suspended sediment yields for Redfish and Laird Creeks, and runoff for Redfish Creek, for the 10-year period of record. The 2002 yield for Laird Creek is missing, as bedload movement interfered with the automatic pump sampler.

Laird Creek exceeded that of Redfish Creek, and bedload movement in the creek interfered with turbidity measurement and automatic sample collection.

5.3. Sediment sources

Estimates of the contribution of sediment from road erosion have been made on several occasions in Redfish Creek watershed, and in all years in the Gold Creek study. These estimates are subject to considerable approximation and error, the greatest of which is the estimation of the delivery ratio (the proportion of eroded sediment which is delivered to the stream channel system). In the Gold Creek tributaries, the entire road network was surveyed each year. In Redfish Creek, in most years erosion surveys were conducted only on a small proportion of the road network which was judged to produce the greatest amount of sediment, and the remainder of the road network was classified on a simple low–moderate–high erosion potential scale (Henderson et al., 1999). An estimate was then made by extrapolation of the total sediment production for the watershed.

Table 4 summarizes the results of the road erosion surveys. For Gold Creek, the delivery ratios are very low, and despite the high road density (2.0 km^{-1} for GA, compared to 0.7 km^{-1} for Redfish Creek), the estimated sediment contribution from roads is only about 0.05 to 0.2 T/km^2/year. In 1998, 2.9 km of new road was built in the GA watershed, and all the roads were used for logging in 1998 and 1999. The data in Table 4 clearly show a trend of declining sediment production from roads in the years following construction and logging. This trend can be explained by revegetation of road cuts and ditches, reduced road traffic volumes following completion of logging operations, and armouring of the road surfaces by coarse gravel following erosion of easily removed fine material.

In Redfish Creek, most of the road network is old, although two short spurs were built in 1992 and 1994, and about 5 km of road was maintained and used for logging in 1997. In May 1993, a major erosion event

Table 4
Summary of road erosion surveys

Year	1997	1998	1999	2000	2001	2002
Redfish Creek						
Source erosion (T)		56				
Delivered to stream (T)	155[a]	18[b]	90[c]	60[c]		
Delivered to stream (T/km^2)	5.9	0.7	3.4	2.3		
Gold Creek tributary GA						
Source erosion (T)			23	12	4	8
Delivered to stream (T)			0.46	0.29	0.12	0.16
Delivered to stream (T/km^2)			0.18	0.11	0.05	0.06

[a] From Henderson et al. (1999); delivery ratio may be overestimated.
[b] From Toews and Henderson (2001).
[c] Extrapolated from survey of part of the road system.

occurred due to a blocked culvert, causing at least 100 T of sediment to be eroded from a short section of road, and at least 10 to 20 T of fine sediment were delivered to the creek (Jordan and Commandeur, 1998). Since then, considering the erosion surveys that were made, as well as other sporadic observations, it is estimated that approximately 20 to 200 T of sediment are eroded from the road system each year. Of this, about 5 to 50 T of fine sediment (silt and fine sand) may be delivered to the creek, as well as a similar amount of bedload (coarse sand and fine gravel). Most of the sediment is produced from relatively short sections of road, which have more erodible soils than average and which have high connectivity to creeks (Fig. 11). Some maintenance practices, especially grading the road surface and ditches, greatly increase the production of sediment from roads (Jordan, 2001).

In Redfish Creek watershed, one 7 ha cutblock was logged in 1991. Soil erosion was monitored in this cutblock beginning in 1992 (Jordan and Commandeur, 1998); this showed sediment eroded in the cutblock declined from 3.2 to 0.3 T over the following 4 years, of which only a negligible amount (about 0.01 T) was delivered to the creek. An erosion survey was conducted in a 20 ha cutblock which was logged in 1997 and 1998; this showed that no detectable erosion (beyond minor local soil disturbance) or sediment delivery had taken place. In Gold Creek, in the GA tributary, four cutblocks totaling 42 ha were logged in 1998–1999. Inspection of these cutblocks showed that, as in Redfish Creek, no detectable sediment production occurred (Fig. 12).

The results of this study, as well as observations on the impacts of forestry operations on streams throughout the region by the author and others (Jordan, 2001; Toews and Henderson, 2001) have shown that sediment produced from logged areas is negligible compared to that produced by roads. Unlike some other regions such as coastal California where high rates of erosion have been noted following logging (Keppeler et al., 2003), in this region rainfall intensities are typically low, and most runoff and erosion events occur during the snowmelt season. Overland flow in logged areas during rainfall or snowmelt events occurs only where subsoil is exposed, such as on roads, ditches, and skid trails. Forest harvesting practices which are typically employed in this region, including keeping soil disturbance below specified limits during logging, recontouring of skid trails following logging, and leaving unlogged buffers adjacent to streams, limit erosion from logged areas and delivery of any eroded sediment to streams.

The geomorphic event associated with logging and forest roads which has potentially the greatest impact on the sediment budget is landslides. No significant landslides occurred in either Redfish Creek or Gold Creek during the course of the study. However, in about a 10-year period before the study, five landslides occurred from roads in Redfish Creek, two of which deposited an

Fig. 11. Most of the development-related sediment in Redfish Creek watershed comes from erosion of the road surface and ditches during snowmelt runoff. Road surface erosion can be estimated by measuring the dimensions of eroded rills.

Fig. 12. Clearcut in Gold Creek watershed, 2 years after logging. The ground surface and recontoured skid trails do not generate overland flow, and no measurable erosion has occurred since logging.

estimated 1000 to 2000 T of sediment in the creek. If we assume that about 500 T of this was suspended sediment, and the period of development activity over which they occurred is 20 years, this represents an average contribution of 25 T/year, comparable to the average contribution from road surface erosion. However, the average contribution of sediment from landslides is a risk, not an actual annual amount of sediment; in most years, landslides contribute no sediment, but there is a risk that on rare occasions, a landslide will occur, which will dominate the sediment budget for that year.

5.4. Bedload yield

No useful quantitative data on bedload movement is available on the main channels of Redfish, Laird, or Gold Creeks. However, bedload yield has been monitored on the small tributaries which have weirs.

On the Redfish Upper tributary, 10 years of measurement of bed material collected behind the weirs gives an average bedload yield of 1.6 T/km^2/year for the lower site (the drainage of which includes roads and cutblocks), and 0.7 T/km^2/year for the upper site (above all development). The lower site may be fairly typical of conditions in the entire watershed, although without data this cannot be verified. The material collected behind the weirs was coarse sand and fine pebbles.

One of the tributaries of Gold Creek, GB, was disturbed by a small debris flow in its headwaters in 1997. As a result, the creek transports large amounts of bedload material during high flows. This was especially evident in 1998 and 2002, when bedload movement and deposition interfered with the pump sampler and turbidity meter. From 1999 to 2002, the volume of material collected behind the weir was measured. This gave an estimated average bedload yield of 0.4 T/km^2/year. Much less bedload movement was observed in the channels of GA and GC. The bed material in these channels is mostly pebbles and small cobbles, which are produced by erosion of the finely fractured sedimentary rocks.

5.5. Dissolved solids

At present, detailed solute yield data are available for Redfish Creek and Gold Creek for only one year, 2002. In Gold Creek, data were collected on each of the three tributaries as well as on the main creek, and they show considerable variability within the watershed, reflecting differences in bedrock geology. The calculated solute yield for the larger Gold Creek watershed for the April–September period is 20 T/km^2, and for the three tributaries, GA, GB, and GC, the solute yields are 35, 20, and 10 T/km^2 respectively. The higher yields for GA and GB are due to a limestone-bearing formation which underlies part of the watershed.

Redfish Creek is underlain by granitic rocks, and the dissolved solids concentration is much lower. However, the precipitation and runoff are proportionately higher, and the resulting solute yield is similar to Gold Creek at 20 T/km^2.

Fig. 13 shows the daily conductivity plotted against mean daily discharge for Redfish and Gold Creeks for 2002. On both creeks conductivity decreases with increasing discharge, reflecting a greater proportion of surface and shallow subsurface flow to higher-conductivity groundwater. The two curves are similar, although the Gold Creek curve has a lower proportional range and a lower rate of change of conductivity, possibly reflecting a greater groundwater contribution. However, several years of data, and more detailed analysis of data from tributary streams, may be necessary to reach any conclusions about runoff generation mechanisms.

5.6. Long-term average sediment and solute yields

The 5 to 10 year record of suspended sediment measurements, the very approximate estimate of bedload

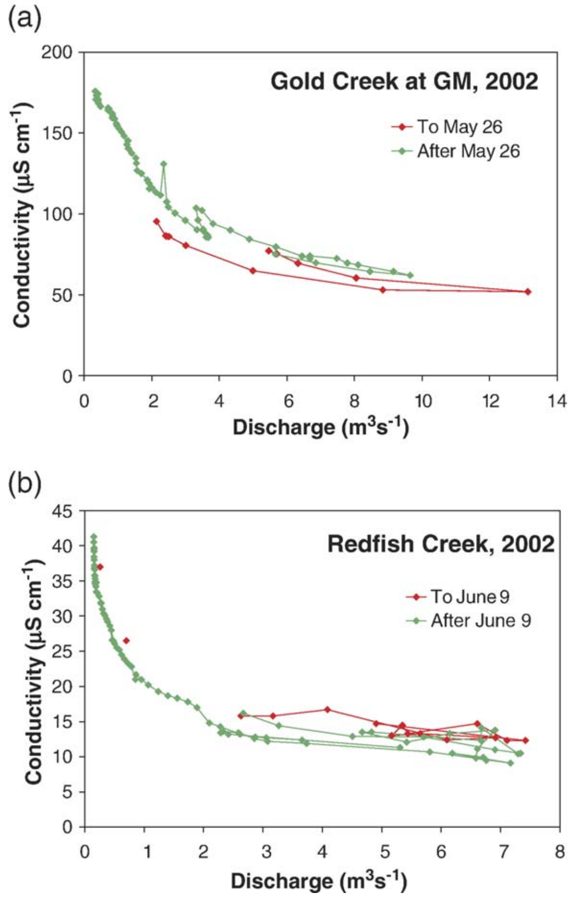

Fig. 13. Conductivity plotted against discharge for Redfish and Gold Creeks for one season. Early season (before peak) and peak-late season are plotted separately. Conductivity is corrected to an arbitrary reference temperature of 15 °C. (a) Gold Creek. (b) Redfish Creek.

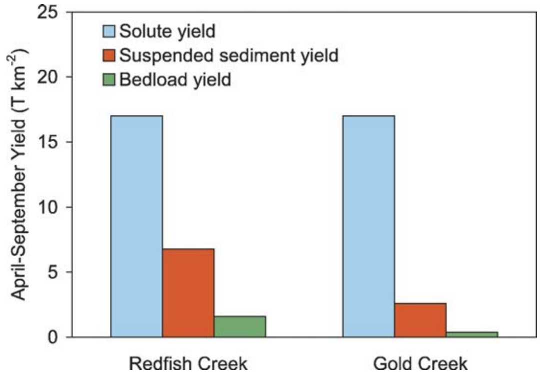

Fig. 14. Estimated average solute, suspended sediment, and bedload yields for Redfish and Gold Creeks for the period of the study.

yield on some tributaries, and the 1-year record of solute yield, enables a reasonable estimate to be made of the total sediment and solute yield for Redfish Creek and Gold Creek. In the case of suspended sediment and solutes, storage opportunities within the watershed are limited, so inputs to the channel system approximately equal the outputs at the watershed mouth.

In the case of bedload, the estimates made here are an approximation of inputs to the main channel from headwater tributaries. Other sediment budget studies have shown that storage of bed material in alluvial deposits along stream channels is many times as great as annual bedload yields, so these estimates give no useful indication of the bedload yield that might be experienced at the mouths of the streams. This is especially the case for Gold Creek, which has a low-gradient storage reach in its main valley, in which most bedload delivered by steeper tributaries is deposited.

Fig. 14 is a graphical representation of the estimated solute and suspended sediment yields, and bedload inputs, for the two watersheds. The suspended sediment yield is based on the average yield for the period of record (giving a reasonably accurate and precise estimate for Redfish Creek, but less so for Gold Creek). The solute yield is based on 1-year record, reduced by a factor of 1.2 to account for the fact that 2002 was an above-average runoff year. Although this is a reasonably accurate calculation for the one year, the year-to-year variation is unknown.

The bedload inputs are order-of-magnitude estimates only. The assumption is made that the bedload yield of one tributary in each watershed is representative of the entire watershed. This may be a reasonable assumption for Redfish Creek, but probably not for Gold Creek. Because of storage in the valley flat, which appears to be aggrading over the long term, it is likely that the bedload yield at the mouth of Gold Creek is much less than the estimate given. Also, because both bedload transport and bedload inputs from slope processes are highly episodic, average bedload yields of tributary streams give little information about the true nature of bedload transport. The two landslides mentioned above (Section 5.3) in Redfish Creek are likely to have delivered, more or less instantaneously, about 20 times as much bedload to the channel as the average bedload input indicated in Fig. 14. On Laird Creek, the bedload movement event of November 1999 probably transported more bedload in a few days than had moved in the previous several decades of "normal" conditions.

Fig. 14 shows that solute yields greatly exceed clastic sediment yields in both watersheds. This conclusion is also made by other studies that have been conducted in relatively inactive geomorphic environments (Slaymaker, 1987).

5.7. Factors affecting sediment yield and sensitivity to development

Data and observations in the Redfish/Laird Creeks and Gold Creek study areas have shown that erosion from roads is the most important development-related impact. In Gold Creek, the sediment contributed from roads is much less than in Redfish Creek, on a watershed area basis and on a road length basis, and this difference does not appear to be due to differences in precipitation or topography.

Comparison of hydrographs for similar sized, headwater drainages (Figs. 7 and 8) shows a great difference in runoff behaviour. The strong diurnal variation during snowmelt which is dominant on the Redfish Creek tributary (RU1 and RU2) is absent on the Gold Creek tributaries (GA, GB, and GC). This is consistent with a runoff mechanism dominated by overland flow and rapid subsurface flow on Redfish Creek, and one dominated by deeper groundwater flow on Gold Creek. The hydrograph of the main Gold Creek (GM station) shows a diurnal cycle during snowmelt, although not as prominent as at Redfish Creek. This suggests that there are saturated areas of high water table, or other areas which generate overland flow, elsewhere in the watershed, probably in the valley bottom.

A related observation is that the road ditches at Gold Creek show little evidence of having carried a continuous flow of water during the spring runoff, compared to Redfish Creek. It appears that at Gold Creek, there is much less seepage of shallow subsurface flow from road cuts, and that most local runoff generated from road surfaces infiltrates into the ditches rather than running to the nearest culvert or creek. Also it appears that most water emanating from culverts infiltrates into the ground within a short distance, rather than forming continuous pathways of overland flow as at Redfish Creek. This difference is probably due to bedrock geology (Jordan, 2001); the sedimentary rocks at Gold Creek are highly fractured, allowing most water from snowmelt to infiltrate into the bedrock, and emerge as relatively slow groundwater discharge. This contrasts with the relatively compact granite at Redfish Creek, where abundant seepage is often observed at the soil–rock interface in road cuts. Also, the GA tributary at Gold Creek is underlain by a rock formation in which limestone and dolomite are abundant, so it is likely that subsurface movement and storage of water in karst-produced cavities takes place.

This leads to the conclusion that bedrock geology may be an important factor in the susceptibility of a watershed to sediment impacts from forest development. In particular, impermeable geology which causes most runoff to be routed to the channel through surface and shallow subsurface flow, results in high connectivity between forest roads and stream channels, and therefore a relatively high risk of sediment delivery from forest roads. Where the geology is more permeable, and streamflow is dominated by groundwater, this risk is lower, at least in upland areas. However, it is important to note that road location plays an important role in the risk of sediment impacts. In a groundwater-dominated watershed such as Gold Creek, if roads in valley-bottom locations intercept springs or other groundwater discharge zones, then the risk of erosion and sediment delivery is high.

6. Conclusions

One of the objectives of this study, and of other studies on sediment budgets and watershed assessment in a forest management context, is to determine whether forest development has had a significant impact on water quality or on stream channel morphology. A related objective is to develop procedures to assess the sensitivity of a watershed to such impacts.

Two premises are presented here, to help interpret the results of this study. The first premise is that sensitivity of a watershed to development-related impacts depends on the background level of geomorphic activity in the watershed. A highly active watershed, for example one with frequent mass movement activity or which contains glaciers, will be less sensitive to a disturbance of a given magnitude than a watershed which lacks such activity. For example, a road erosion event or a landslide which contributes 500 T of sediment to a creek channel, in a watershed with an average background suspended sediment yield of 100 T/year (such as Redfish Creek), will have a major impact both on water quality and the stream channel. However, a similar event in a watershed of similar size with a background yield of several thousand T/year is likely to have only a minor impact.

The second premise is that the background sediment yield of a watershed, measured or estimated, can be used as a benchmark against which to compare a development-related sediment source, and to assess its significance. The following order-of-magnitude guidelines are suggested:

- sediment input is 1% of background—impact is insignificant
- sediment input is 10% of background—impact is probably significant
- sediment input is 100% of background—impact is highly significant.

In the first case, the sediment input is much less than the measurement error of sediment yield. Although it might be observed at the source location (for example, a road washout), it would probably be immeasurable at the watershed outlet. In the second case, the sediment input would probably be measurable, and depending on its timing and location, it may have a detrimental impact on water quality for a short time, or on the stream channel at some location. In the third case, the increase in sediment supply is probably comparable to the natural range of variability of annual sediment yield. If it is a one-time instantaneous event, such as a landslide, it is likely to have a serious (although perhaps short-lived) impact on water quality or channel condition. If it is a continuous, recurring event (such as annual erosion from a newly constructed road network) then it may result in a long-term detrimental impact to water quality or stream channel morphology. The guidelines suggested above are based on suspended sediment inputs; the same concept is applicable to coarse sediment, although because quantitative data on bedload is lacking, the suggested numbers may not apply. The premise applies to watersheds such as Redfish, Laird, and Gold Creeks which are not lake-controlled; watersheds which have large lakes or wetlands which provide storage for sediment may be relatively less sensitive to impacts from sediment inputs.

Applying these criteria, both Redfish Creek and Gold Creek should be sensitive to development-related sediment impacts, as they have low background suspended sediment yields, compared to most of British Columbia and to mountain areas elsewhere. The data on sediment yield and sediment sources suggest that at Redfish Creek, the impact of forest development, and forest roads in particular, on water quality has been significant. At Gold Creek, the impact (at least in the tributary streams studied) has been insignificant. This difference is largely due to differences in geology; the groundwater-dominated runoff regime at Gold Creek reduces the risk of sediment delivery to streams.

In both study areas, solute yield is greater than clastic sediment yield. Solute yields are similar in both areas, despite differences in geology. Higher precipitation and runoff in the granitic western area offset the more soluble sedimentary geology of the eastern area.

Bedload yield is the smallest component of the sediment budget in both study areas. However, the 1999 event on Laird Creek emphasizes the importance of episodic flood and landslide events on the bedload sediment budget in these steep mountain watersheds.

This study emphasized the suspended sediment component of the sediment budget, which is of prime importance for water quality concerns. The main uncertainty in the study was bedload storage and yield. Bedload transport and stream channel morphology are relevant for aquatic habitat concerns, and changes in bedload transport and bank erosion due to possible increases in peak flow resulting from forest harvesting can provide an additional source of suspended sediment. For this reason, future research on the effects of forest development on the sediment budget should emphasize stream channel morphology and the bedload component of the sediment budget.

Acknowledgements

This study owes a great deal to the work of Emilee Fanjoy, research technician with the Nelson Forest Region until 2003, who was responsible for most of the instrument installation and maintenance, data logger programming, and other field tasks. Many college and university students were hired over the course of the study, and provided valuable assistance with field and lab work. Paul Commandeur, formerly of the Canadian Forest Service, and Greg Henderson of Henderson Environmental Consultants participated in some aspects of the study, particularly estimation of sediment sources from roads and logged areas. David Toews and David Gluns, my research colleagues with the Ministry of Forests in Nelson, worked on related hydrology studies, and provided useful advice and review during the progress of this study. Forest Renewal BC provided research funding from 1996 to 2002. The paper benefited from reviews by Ellen Petticrew, Daniel Evans, Dan Hogan, and an anonymous reviewer.

References

Beschta, R.L., 1978. Long-term sediment production following road construction and logging in the Oregon Coast Range. Water Resources Research 14, 1011–1016.

Boyer, D., Jordan, P., 2001. November 1999 fall storm: Kootenay region. Changing Water Environments: Research and Practice. CWRA BC Branch Conference Proceedings, May 8–11, 2001, Whistler, B.C., pp. 24–33.

Church, M., Slaymaker, O., 1989. Disequilibrium of Holocene sediment yield in glaciated British Columbia. Nature 337, 452–454.

Church, M., Kellerhals, R., Day, T.J., 1989. Regional clastic sediment yield in British Columbia. Canadian Journal of Earth Sciences 26, 31–45.

Dietrich, W.E., Dunne, T., 1978. Sediment budget for a small catchment in mountainous terrain. Zeitschrift für Geomorphologie (Suppl. 29), 191–206.

Henderson, G.S., Tutsch, M., Jordan, P., 1999. a rapid road erosion survey technique. Unpublished report, British Columbia Ministry of Forests, Nelson Forest Region.

Holland, S.S., 1964. Landforms of British Columbia: A Physiographic Outline. British Columbia, Department of Mines and Petroleum Resources, Bulletin 48, Victoria, B.C.

Hudson, R., 2001. Storm-based sediment budgets in a partially harvested watershed in coastal British Columbia. British Columbia, Ministry of Forests, Vancouver Forest Region, TR-009.

Jordan, P., 1996. Turbidity and suspended sediment measurements using OBS meters, West Arm Demonstration Forest sediment budget study. Proceedings, The Second Automatic Water Quality Monitoring Workshop, Richmond, B.C., Feb. 12–13, 1996. Environment Canada and British Columbia, Ministry of Environment, Lands and Parks, pp. 1–10.

Jordan, P., 2001. Sediment budgets in the Nelson Forest Region. In: Toews, D.A.A., Chatwin, S. (Eds.), Watershed Assessment in the Southern Interior of British Columbia: Workshop Proceedings, March 9–10, 2000, Penticton, British Columbia. British Columbia, Ministry of Forests, Research Branch, Working Paper 57, Victoria, B.C., pp. 174–188.

Jordan, P., 2002a. West Arm Demonstration Forest: Sediment Budget. Final report, FRBC Research Award no. KB96066-RE. Unpublished report submitted to Forest Renewal BC, Victoria, B.C.

Jordan, P., 2002b. Sediment Budgets of Community Watersheds in the Nelson Forest Region. Final report, FRBC Research Award no. KB96047-RE. Unpublished report submitted to Forest Renewal BC, Victoria, B.C.

Jordan, P., Commandeur, P., 1998. Sediment research in the West Arm Demonstration Forest, Nelson, B.C. In: Alila, Y. (Ed.), Mountains to Sea: Human Interaction with the Hydrologic Cycle. Proceedings, Canadian Water Resources Association, 51st Annual Conference, June 10–12, 1998, Victoria, B.C., pp. 348–363.

Jordan, P., Slaymaker, O., 1991. Holocene sediment production in the Lillooet River basin, British Columbia: a sediment budget approach. Géographie Physique et Quaternaire 45, 45–57.

Jungen, J.R., 1980. Soil Resources of the Nelson Map Area. British Columbia, Ministry of Environment, Resource Analysis Branch, RAB Bulletin 20, Kelowna, BC.

Kelsey, H.M., 1980. A sediment budget and an analysis of geomorphic process in the Van Duzen River basin, north coastal California, 1941–1975: summary. Geological Society of America Bulletin Part 1 (91), 190–195.

Keppeler, E., Lewis, J., Lisle, T., 2003. Effects of forest management on streamflow, sediment yield, and erosion, Caspar Creek Experimental Watersheds. The First Interagency Conference on Research in the Watersheds, 27–30 October 2003, Benson, AZ. U.S. Department of Agriculture, Agricultural Research Service, pp. 77–82.

Macdonald, J.S., Beaudry, P.G., MacIsaac, E.A., Herunter, H.E., 2003. The effects of forest harvesting and best management practices on streamflow and suspended sediment concentrations during snowmelt in headwater streams in sub-boreal forests of British Columbia, Canada. Canadian Journal of Forest Research 33, 1397–1407.

Madej, M.A., 1997. Residence times of channel-stored sediment in Redwood Creek, northwestern California. In: Beschta, R.L., Binn, T., Grant, G.E., Ice, G.G., Swanson, F.J. (Eds.), Erosion and Sedimentation in the Pacific Rim International Association of Hydrological Sciences, Publ., vol. 165, pp. 429–438.

Megahan, W.F., Seyedbagheri, K.A., Mosko, T.L., Ketcheson, G.L., 1986. Construction phase sediment budget for forest roads on granitic slopes in Idaho. In: Hadley, R.F. (Ed.), Proc., Drainage Basin Sediment Delivery International Association of Hydrological Sciences, Publ., vol. 159, pp. 31–39.

Reid, L., Dunne, T., 1984. Sediment production from forest road surfaces. Water Resources Research 20, 1753–1761.

Reid, L.M., Dunne, T., 1996. Rapid Evaluation of Sediment Budgets. Catena Verlag GMBH, Reiskirchen, Germany.

Roberts, R.G., Church, M., 1986. The sediment budget in severely disturbed watersheds, Queen Charlotte Ranges, British Columbia. Canadian Journal of Forest Research 16, 1092–1106.

Ryder, J.M., 1981. Biophysical Resources of the East Kootenay Area: Terrain. British Columbia, Ministry of Environment, Assessment and Planning Division, APD Bulletin 7, Victoria, B.C.

Slaymaker, O., 1987. Sediment and solute yields in British Columbia and Yukon: their geomorphic significance reexamined. In: Gardiner, V. (Ed.), International Geomorphology 1986, Part 1. 1st International Geomorphology Conference, Manchester, Sept. 1985. John Wiley and Sons, pp. 925–945.

Swanson, F.J., Janda, R.J., Dunne, T., Swanston, D.N. (Eds.), 1982. Sediment Budgets and Routing in Forested Drainage Basins. U.S. Dept. of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station, General Technical Report PNW-141.

Toews, D.A.A., Henderson, G.S., 2001. Using sediment budgets to test the Watershed Assessment Procedure in southeastern British Columbia. In: Toews, D.A.A., Chatwin, S. (Eds.), Watershed Assessment in the Southern Interior of British Columbia: Workshop Proceedings, March 9–10, 2000, Penticton, British Columbia. British Columbia, Ministry of Forests, Research Branch, Working Paper 57, Victoria, B.C., pp. 189–208.

Winkler, R.D., Spittlehouse, D.L., Heise, B.A., Giles, T.R., Alila, Y., 2003. The upper Penticton creek watershed experiment: a review at year 20. Water Stewardship: How Are We Managing? Proceedings, 56th Canadian Water Resources Association Conference, June 11–13, 2003, Vancouver, B.C., pp. 51–58.