

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, Canada¹

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Abstract: This paper examines suspended sediment concentration and stream discharge during freshet in three small sub-boreal forest streams (<1.5 m in width) in the central interior of British Columbia for 1 year prior to (1996) and for 5 years following forest harvesting (1997–2001). Harvesting prescriptions in a 20-m strip beside one stream required complete removal of merchantable timber (>15 cm diameter at breast height (DBH) for pine and >20 cm for spruce), while all stems <30 cm DBH were retained beside a second stream. A third stream remained unharvested as a control. The two riparian treatments were prescribed to test the efficacy of current British Columbia legislation that allows for varying amounts of riparian retention as best management practices for the management of windthrow. Both treated watersheds were clear-cut harvested (approximately 55% removal) in January 1997, and in the following year, temporary access roads were deactivated, including two stream crossings in the low-retention watershed. An increase in peak snowmelt and total freshet discharge was first noted in the second spring following harvest in both treatments and remained above predicted in all subsequent years. Suspended sediment also increased during freshet following harvest but returned to levels at or below preharvest predictions within 3 years or less in the high-retention watershed.

Résumé : Ce manuscrit examine la concentration des sédiments en suspension et le débit de crue dans trois petits cours d'eau de la forêt sub-boréale (<1,5 m de largeur) dans le centre de l'intérieur de la Colombie-Britannique, durant 1 an avant (1996) et 5 ans après la récolte de la forêt (1997–2001). La prescription de récolte dans la bande de 20 m près d'un cours d'eau impliquait l'enlèvement total des tiges marchandes (>15 cm au diamètre à hauteur de poitrine (DHP) pour les pins et >20 cm pour les épinettes), tandis que toutes les tiges <30 cm au DHP étaient retenues le long d'un deuxième cours d'eau. Un troisième cours d'eau qui n'avait subi aucune intervention a servi de témoin. Les deux traitements riverains ont été prescrits afin de vérifier l'efficacité de la législation actuelle de la Colombie-Britannique qui permet la rétention d'une quantité variable comme meilleure pratique d'aménagement pour les chablis. Les deux bassins traités ont subi une coupe à blanc (environ 55 % de récolte) en janvier 1997 et les chemins d'accès temporaires, incluant deux traverses de cours d'eau dans le bassin avec faible rétention, ont été désactivés. Une augmentation de la pointe de fonte et de l'écoulement total de crue a d'abord été observée durant le deuxième printemps après la coupe dans les deux traitements et est demeurée au-dessus de la prédiction durant toutes les années subséquentes. La concentration des sédiments a aussi augmenté durant les crues suivant la récolte mais est revenue aux mêmes valeurs, ou en deçà des prédictions pré-récolte, en 3 ans ou moins dans le bassin à haute rétention.

[Traduit par la Rédaction]

Introduction

Our understanding of the impact of forest harvesting on sediment production and hydrologic response in small water-

heds is based largely on coastal, rain-dominated watersheds (e.g., Carnation Creek, Hartman and Scrivener 1990) or interior systems in southern locations in Canada or the United States (e.g., Colorado, Troendle and King 1987). These and

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other studies describe harvesting-induced increases to peak flow, daily discharge, and freshet water yield as a consequence of changes to several processes (Van Haveren 1988), including reduced precipitation interception and transpiration with the loss of foliage (Adams et al. 1991; Spittlehouse 1998) and increased snowpack accumulation in cutblocks (Troendle and King 1987; Heinonen in press). Compacted soils associated with logging roads and skid trails will decrease water infiltration to the soil and may redirect both surface and subsurface water flow to the stream sooner and in larger quantities following harvesting (Luce and Cundy 1994; Hutchinson and Moore 2000). Hydrologic timing may also be altered when a reduction in canopy cover exposes the snow surface to greater solar radiation and airflow causing more rapid melting. Forest regeneration is expected to mitigate the effects of harvesting and allow hydrological characteristics to return to preharvest conditions, often referred to as hydrologic recovery. Recovery in peak flows and water yields following harvesting have been reported in both coastal and interior settings (Troendle and King 1985; Hicks et al. 1991).

Following forestry operations, sediment sources become more available and suspended sediment appears in elevated levels in local watercourses. Suspended sediment concentration is positively correlated with water discharge but is subject to hysteresis during events and on a seasonal time scale, particularly when sediment supply sources are limited (Paustian and Beschta 1979; Cheong et al. 1995). Suspended sediment concentrations will increase following forestry operations and their persistence may depend on hydrologic recovery (Lewis et al. 2001). Most studies that detect a post-forestry increase in sediment can trace the source to a specific activity such as road and (or) ditch construction, slash burning, or slope failure (Slaney et al. 1977; Jordan 2001; Hudson 2001). While in use, forest roads can also generate large amounts of suspended sediment (Reid and Dunne 1984). The episodic nature of sediment supply processes (e.g., in-stream erosion or road runoff during high flows), the tendency for the contribution of some sediment sources to lag behind the land-use impact (e.g., upslope failures following root decomposition), and high background levels from natural sources complicate the examination of the impacts of forestry operations on suspended sediment concentrations and their persistence (Henderson and Toews 2001).

While it is commonly acknowledged that forestry activities can have an influence on hydrological budgets and suspended sediment concentrations, much of our knowledge is based on research from large systems in coastal or southern interior settings. Unlike southern watersheds, hydrological regimes in northern boreal settings tend to be snowmelt dominated and have lower levels of precipitation, which has consequences for both peak flow timing and suspended sediment production. First-order streams tend to store sediments for briefer periods and have lower sediment yields than higher order systems in valley bottoms where glacial deposits prevail (Church et al. 1989; Church 1995). Small streams are conduits for water, sediment, nutrients, and biota, connecting upland catchments to forest and aquatic ecosystems at lower elevations. Their ecological importance has recently been recognized (e.g., Sidle et al. 2000), but they currently only receive minimal protection by most land-use regula-

tions despite harvesting routines that in one pass can commonly encompass entire catchment areas (Young 2000). An examination of harvesting impacts in small interior watersheds in sub-boreal forests is essential.

The proliferation of riparian zone management regulations in the Pacific Northwest of North America (Young 2000) is evidence to the importance that society places on riparian forests for providing a link between terrestrial and aquatic ecosystems and protecting water quantity and quality (Gregory et al. 1991; Gilliam 1994; Brosfoske et al. 1997). The riparian zone may include vegetation that shades the stream, intercepts sediment flow, or contributes organic matter to the floodplain or channel (e.g., leaves, wood, dissolved materials). They may also contain many of the highest nontimber resource values in the natural forest (British Columbia Ministry of Forests 1995). The *Forest Practices Code* of British Columbia legislation specifies riparian management area widths of 20 and 30 m for streams with bankfull widths of less than 3 m without fish and streams less than 1.5 m with fish, respectively. Harvesting within the riparian management area (RMA) may follow best management practice (BMP) objectives that specify the retention of all trees within 10 m of the stream bank on windfirm sites. In areas prone to windthrow, a variety of variable retention prescriptions are permissible if as many windfirm trees as possible are maintained. The application of these objectives is flexible and subject to various interpretations and frequently result in the removal of all commercial vegetation. Consequently, they have proven to be controversial, and their effectiveness for protecting aquatic ecosystems has been questioned.

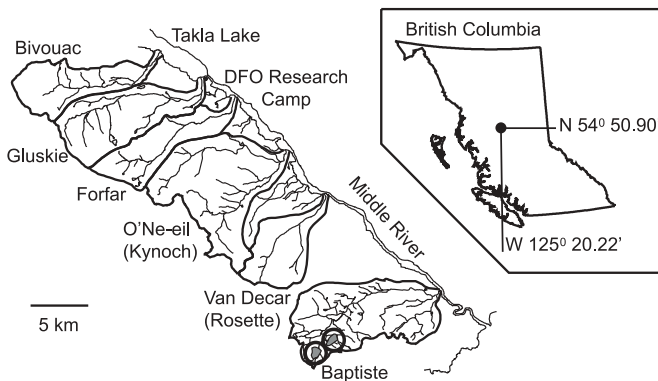
This paper examines flow volume and timing and suspended sediment concentrations during spring freshet in three first-order tributaries in the sub-boreal forests of central British Columbia. The experiment incorporated variable retention forest harvesting techniques to RMAs adjacent to two of the creeks to test the efficacy of the *Forest Practices Code*. Data collection began 1 year prior to harvesting in the treatment watersheds and an unaltered watershed and continued annually for 5 years following harvest to provide insight into both annual patterns of natural variation and the persistence of forestry-induced hydrologic and sediment disturbances. The influence of stream crossings and access roads in one of the treatment watersheds was also examined.

Materials and methods

Study location

This study was conducted in three small headwater tributaries of Baptiste Creek, located near the north end of Trembleur Lake in the Fort St. James Forest District in the interior of British Columbia (Figs. 1 and 2). Present-day landforms and surficial materials are largely a result of the last Pleistocene glaciation, known as the Fraser Glaciation. Terrain throughout most of the watershed is gently to moderately sloping; hummocky or rolling in detail; and generally bedrock-controlled, including hummocks and glacial lineations (Collett and Ryder 1997). The sites are at the northern end of the Sub-Boreal Spruce Biogeoclimatic Zone (Engelmann Spruce – Subalpine Fir Zone at high elevations). Average annual precipitation in the experimental

Fig. 1. Stuart–Takla Fisheries–Forestry Interaction Project study area showing the experimental watersheds. The headwater stream study cutblocks are denoted with circles in the Baptiste watershed.

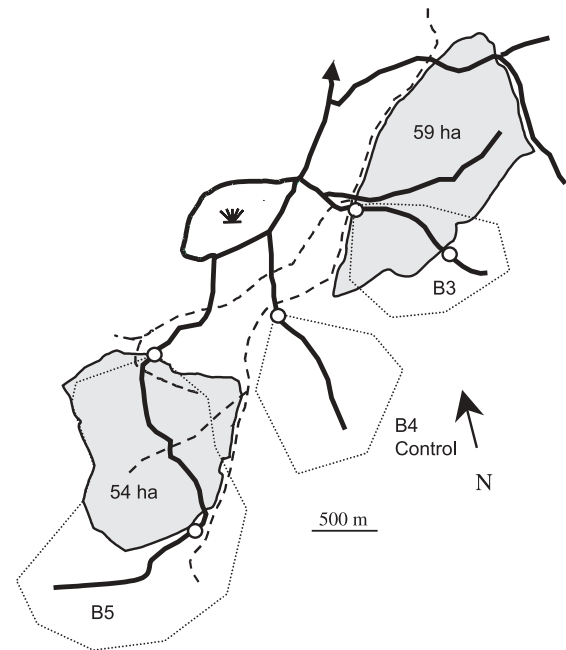


watersheds is 500 mm, with 160–400 mm falling as snow. Peak discharge is largely controlled by spring snowmelt in late April to early June depending on the year, and lowest flows occur during winter. Ice usually covers the streams in November, and the growing season is short compared with that of the coastal zones in British Columbia. This research is a component of the Stuart–Takla Fisheries–Forestry Interaction Project, a multidisciplinary research program established to investigate forestry treatments in watersheds near Takla Lake (Macdonald et al. 1992) (Fig. 1).

Study design

The experimental design is based on the classic paired-watershed approach (Bates and Henry 1928) applied to three first-order creeks (Table 1). Approximately 55% of two of the three watersheds upstream of the hydrologic stations on each stream were harvested following a low riparian retention treatment in B5 (removal of all merchantable timber, >15 cm DBH for pine and >20 cm for spruce within 20 m of the stream) and high riparian retention treatment in B3 (removal of merchantable timber >30 cm DBH within 20 m of the stream) (Table 2). Both cutblocks were approximately 55 ha. The B5 cutblock was contained entirely within the B5 watershed, whereas the B3 cutblock extended into two adjacent watersheds (Fig. 2). The B4 watershed was left unlogged to serve as a control. Initially, the high-retention treatment preserved approximately half of the original canopy cover and nearly twice that of the low-retention treatment. Widespread windthrow in the winters of 1997, 1998, and 1999 along the road right-of-ways and in B3 reduced canopy density to below 10% (Macdonald et al. 2003). Harvesting followed established techniques and was performed by Canadian Forest Products Ltd. using feller–bunchers and skidders. Felled trees were skidded downslope to landings and existing haul roads. Limbs and residual wood debris was left on the snow following harvest. A 5-m machine exclusion zone along the streambanks and an effort to fall and yard riparian trees away from the streams were generally successful at maintaining riparian understory vegetation in both watersheds. On B5, two road crossings using culverts were the only locations a haul road crossed any of the creeks above a hydrologic station (Fig. 2). One of these culverts

Fig. 2. Small stream study sites in the Baptiste watershed. Thick lines denote watercourses, broken lines denote roads, dotted lines denote flume catchment boundaries, and circles denote sampling stations. Cutblocks are shaded, with their size (ha) noted.



was removed during road deactivation activities in the fall of 1997, causing substantial soil disturbance and exposing steep, unstable banks 3 m in height. No erosion control measures were taken to reduce sediment delivery at this crossing.

At each hydrologic station in the three watersheds, a 9-in. (1 in. = 2.54 cm) Parshall flume (Parshall 1936) was installed in the stream immediately below the cutblocks (B3, B5) and at a similar elevation in B4. Six-inch Parshall flumes were also installed on B3 and B5 just above the upper edge of the cutblocks (data not shown). Stage height was measured using a 1-m capacitive water-depth probe. The concentration of suspended sediments in the water column passing through the flume was measured using a combination of an optical backscatter turbidity probe and a pump-driven water sampler. Measurements of stage height and turbidity were made every 10 s and averaged over a 15-min period. The collection of water samples was electronically triggered at preset turbidity levels, allowing intensive sampling during periods of high turbidity and very limited sampling during periods of clear flows. Total suspended sediment (TSS) samples were collected on filters, dried and weighed, and used to establish a relationship between the concentration of suspended solids and the turbidity readings obtained from the turbidity probes. TSS included both organic and inorganic material.

During the snowmelt period (defined by the period that flow exceeded base flow from graphical analysis), the flume sites were visited approximately weekly to maintain the instruments, collect water samples, and reset the samplers. Snowpack water equivalency was measured several times each spring in a road clearing near the upper boundary of B5. During site visits, we walked the length of the harvested

Table 1. Physical characteristics of the three study watersheds.

Water-shed	Size (ha)	Flume		Elevation range (m)	Channel length (m)	Stream gradient (degrees)	Average channel width (m)	Surficial materials ^b	Dominant texture
		catchment area (ha) ^a	Aspect						
B3	43	29	NW	980–1340	1373	26	0.60	Basal till	Silty-sand
B4	48	36	NW	980–1340	1200	30	0.85	Basal till	Silty-sand
B5	150	79	N	980–1300	2093	7	1.38	Basal till	Silty-sand

^aCorresponds to the area of the watershed upstream of the sampling flume.

^bTypically, the basal till consists of a fine-grained matrix of sand (about 45%), silt (about 37%), and clay (about 18%) surrounding and supporting clasts of a variety of sizes, shapes, and rock types.

Table 2. Forest types, logging operations, and riparian treatments in the three study watersheds.

Watershed	Dominant tree species ^a	% of watershed clear-cut harvested	Length of channel harvested (m)	Riparian treatment ^b
B3	Bl, Sx	55	900	High retention
B4	Bl, Sx, Pl	Unlogged	Unlogged	Unlogged
B5	Bl, Sx, Pl	53	1060	Low retention

^aBl, *Abies lasiocarpa* (Hook.) Nutt. (alpine fir); Sx, *Picea glauca* × *Picea engelmannii* (hybrid white spruce); Pl = *Pinus contorta* Dougl. ex Loud. var. *latifolia* Engelm. (lodgepole pine).

^bSee text for treatment prescriptions.

creeks in an attempt to locate any point sources of sediment entering the creeks.

Preharvesting data collection began in the spring of 1996. The cutblocks were harvested in January 1997. Post-harvesting data have been collected at the flume sites since that time. The initial results describing the effects of the first year after harvest are presented in Beaudry (1998a). This report summarizes all of the results to date, including observations for an additional 4 years following harvest (i.e., 1998–2001).

Analysis methods

Stream discharge was computed using the stage–height relationship unique to the two Parshall flume sizes according to predetermined regression equations (Parshall 1936). Optical backscatter turbidity measurements were converted to suspended sediment concentration at all sites and all water levels encountered using the following linear regression:

$$\text{TSS} = 0.44(\text{OBS}) + 1.25,$$

$$R^2 = 0.64, \text{ SE} = 4.17, n = 32$$

where TSS is the concentration of total suspended solids (ppm) and OBS is the signal (mv) sent from the turbidity probe. This method for calibrating the OBS signal was used in previous analyses (Beaudry 1998b).

Regression analysis was used to generate preharvest relationships during the snowmelt period between the control stream (B4) and the two treatment streams (B3 and B5) to estimate expected untreated levels for both stream discharge and TSS during the treatment periods. Prediction limits (95%) about the estimated values were included to assist in evaluating the alteration in values following harvest (Sokal and Rohlf 2000). This approach was used by Hornbeck et al. (1993). The regression residuals met normality and homo-

scedasticity requirements, so no transformations were performed. Owing to the brevity of the freshet and the single year of available pretreatment data, we were forced to use daily average values and tested for autocorrelation using the Durbin–Watson statistic (d) at $\alpha = 0.05$. If present, autocorrelation violates the parametric assumption of independence among replicates and leads to an underestimation of error level in the regression predictions. Positive autocorrelation was present in the TSS regressions where d was less than the lower significance limit d_L ($d = 0.46$ – 0.89 ; $n = 25$, $d_L = 1.29$, $d_U = 1.45$) but was inconclusive for the discharge regressions where d fell between the upper and lower significance limits for the d statistic ($d = 1.32$ – 1.33 ; $n = 25$, $d_L = 1.29$, $d_U = 1.45$), indicating that the TSS regression predictions presented are less precise than the least-squares confidence limits imply. Additional preharvest years and data would have alleviated this problem and allowed an autoregressive correction while also providing more insight into natural variability patterns among years for both discharge and TSS. However, constraints to harvesting timing imposed by the forest company were beyond our control.

Results

During spring freshet of 1996, both treatment watersheds (B3, B5) had preharvesting hydrographs and suspended sediment relationships that closely matched those of the control watershed (B4) ($r^2 = 0.84$ – 0.98 , Table 3; Figs. 3 and 4). There were differences in mean daily freshet discharge during the years following harvesting, particularly in B5 (comparison of regression coefficients among years, Table 3; % yield, Table 4; Fig. 3). Peak discharges increased as well and followed a pattern similar to mean daily water discharge during the entire freshet period (Table 4). However, a 1-year delay in these effects after harvesting coincided with the large amounts of logging slash observed on the snow following harvesting.

The highest peak discharge occurred in 1997 in all three watersheds, coincident with the largest snowpack in the 6 years of observation (Figs. 3 and 5), although the B5 data set is incomplete because of datalogger failure during highest flows. The largest increase in mean daily discharge during freshet relative to the control stream exceeded 100% and occurred in B5 in 2000 and 2001, although 2001 calculations are based on a nonsignificant regression relationship (Table 4). Neither of these years had abnormally large spring snowpacks based on our 6-year database. The increase in each year's water discharge in B3 (the high riparian retention treatment) was lower than that in B5 but, like in B5,

Table 3. Regression equations describing the discharge and total suspended sediment (TSS) relationships between the high- (B3) and low-retention (B5) treatment watersheds and the control (B4) before harvesting operations.

Relationship	1996	1997	1998	1999	2000	2001
Discharge						
B3 vs. B4 ($y = 0.328x + 0.0055$) ^a						
RC	0.328	0.285	0.514	0.536	0.496	0.275
r^2	0.92	0.88	0.70	0.80	0.94	0.66
n	25	33	13	43	34	26
B5 vs. B4 ($y = 2.213x + 0.0133$) ^a						
RC	2.213	1.958	4.219	3.875	3.612	1.31 ^b
r^2	0.98	0.80	0.82	0.79	0.84	0.08
n	25	28	13	38	34	26
TSS						
B3 vs. B4 ($y = 1.079x - 1.33$) ^a						
RC	1.079	1.400	1.120	0.438	0.81 ^b	1.200
r^2	0.84	0.92	0.93	0.54	0.21	0.69
n	25	27	13	41	23	17
B5 vs. B4 ($y = 1.021x - 0.48$) ^a						
RC	1.021	1.270	2.323	1.465	0.525	0.812
r^2	0.85	0.58	0.81	0.77	0.62	0.91
n	25	27	13	41	23	17

Note: Regressions were performed for each postharvest year.

Comparison of regression coefficients among years provides insight into the effects of harvesting and recovery time on the response variables. RC, regression coefficient; r^2 , coefficient of determination; n , sample size (days).

^aPreharvest equation is given in parentheses.

^bIndicates a poor relationship between the control (B4) and treatment stream. These values should be interpreted with caution.

was highest in 2001. In the 5 years following harvest, there was no indication of hydrologic recovery in either watershed. The timing of peak flow did not appear to be altered by harvesting. Peak flows generally occurred at the same times as peak flow in B4, the control. On occasion, a bimodal distinction in peak flow occurred in stream B5, with the initial peak relative to B4 advanced by 5 days in 1999 and 14 days in 2001 (Fig. 3).

Prior to forestry operations, peak suspended sediment concentrations in all three watersheds were between 25 and 30 mg/L (1996; Fig. 4). Concentrations increased on the rising limbs of the hydrographs each year in each creek, regardless of the presence of a harvesting treatment, such that equivalent discharges had different sediment loads dependent on their timing (1998 data presented as an example, Fig. 6). Immediately following harvest, more fine sediment was mobilized in both treatment systems than predicted from preharvest relationships (regression coefficients, Table 3; % yield, Table 4; Fig. 4). Windthrow events in the RMAs may have contributed to TSS concentrations, particularly in B3, but this effect was not observed during streamside surveillance. Increased TSS persisted for only 2 years in the high-retention watershed and for 3 years in the low-retention watershed, after which there was a decrease in TSS in both treatments to levels that were frequently below predicted from the preharvesting relationship. This drop in TSS levels to below those predicted by the control stream may also reflect a natural disturbance event in B4 that exposed new sed-

iment sources during the experimental period. The greatest TSS was produced in B5, particularly in the second postharvest year (1998), when a 74% increase in TSS yield was detected during freshet (Table 4). Peak concentrations were in excess of 80 mg/L, more than twice the predicted concentrations (Fig. 4). They occurred in association with discharges that exceeded 0.2 m³/s (Fig. 3) and substantial soil disturbance from the removal during the previous fall (1997) of one of the two culverts in B5.

Discussion

Based on the observed increase in water discharge during freshet following forest harvesting in this study, we can speculate that the cutblocks in the two treatment watersheds accumulated more snow than adjacent forested areas. Heinonen (in press), working in a neighbouring watershed, described snow water equivalent accumulation in a cutblock as typically exceeding forested areas by 51%, based on 6 years of continuous data. Increased snow accumulations are likely responsible for the increase in peak flows and mean daily discharges observed in the treated watersheds. However, this supposition is challenged by an absence of a change to peak flow or mean daily discharge during the first postharvest year. It is possible that our winter harvesting treatments, because they occurred following the period of maximum annual growth (and associated transpiration), did not affect groundwater levels or streamflow until the following winter and spring (Adams et al. 1991; Hicks et al. 1991). This, along with the insulating effect of the slash that was left on the snow following the harvest, may explain the lack of an alteration in freshet output timing or peak discharge in B3 and possibly B5 (where some data were missing) during the first postharvest freshet.

Our 4-year mean estimate of a 59–61% increase in freshet discharge and peak flow for stream B5 (disregarding the 2001 data) is somewhat larger than most published values. Van Haveren (1988) detected a 50% increase in mean daily freshet discharge following the clear-cutting of 100% of an 81-ha watershed in Colorado. In the same region, Troendle and King (1987) reported an average increase in peak flow of 50% following a clear-cut of 36% of a 41-ha watershed. These increases were lower than our estimates from the low riparian retention watershed, but much higher than our estimates from the high riparian retention site, despite Troendle and King examining comparable amounts of timber harvested from a watershed of a similar size. This disparity among studies and between our riparian treatments may simply reflect a natural range of hydrologic response to forest harvesting as a result of inherent differences among watersheds. For instance, the B5 watershed, while equivalent in many characteristics to B3 (Tables 1 and 2), had a slightly different aspect and shallower gradient and, therefore, was exposed to more direct solar radiation, which increased the latent energy to the snowpack (Beaudry and Golding 1987; Berris and Harr 1987). This may have caused greater snowmelt rates and higher peak flows and may have been responsible for the apparent temporal desynchronization of the snowmelt process in the clearcut and forest in 1999 and 2001 (Verry et al. 1983). Moreover, the B5 watershed may have shallower soils and shallower, faster flow paths than the

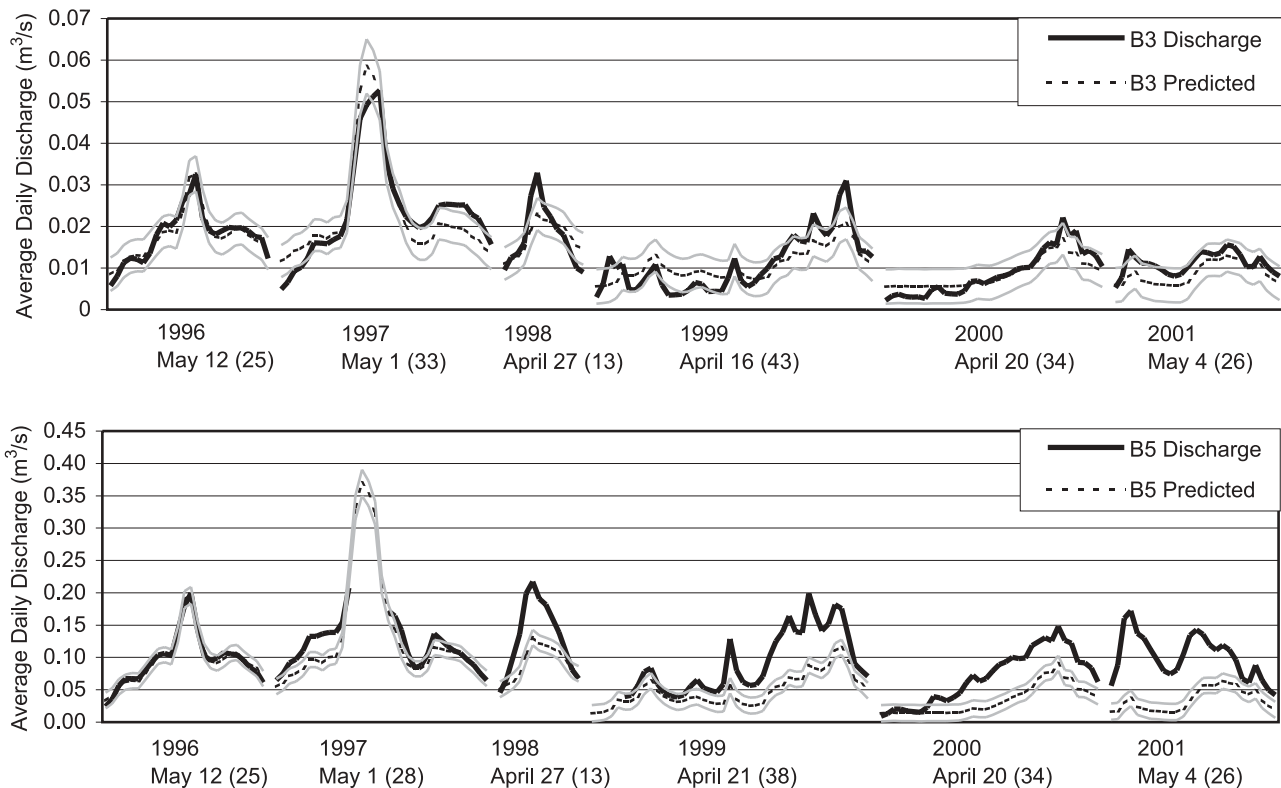
Table 4. Changes in discharge and total suspended sediment (TSS) from predicted levels (according to preharvest regression relations with the control stream, Table 3) following harvesting in both treatment watersheds.

Year	Discharge				TSS			
	B3 vs. B4		B5 vs. B4		B3 vs. B4		B5 vs. B4	
	% yield	% peak	% yield	% peak	% yield	% peak	% yield	% peak
1997	1	2	15	-8	8	42	35	104
1998	3	43	42	66	8	13	74	125
1999	2	50	75	125	-43	-44	46	90
2000	2	30	104	62	-49 ^a	56 ^a	-25	-15
2001	29	20	193 ^a	367 ^a	-50	12	25	3

Note: Changes are expressed as the difference in daily mean between the actual and predicted values, summed for the snowmelt freshet period (% yield in the table). Percent difference in peak levels is also provided. Not all data were available for B5 in 1997.

^aIndicates a poor relationship between the control (B4) and treatment stream. These values should be interpreted with caution.

Fig. 3. Average daily water discharge (m³/s) during the snowmelt freshet period before (1996) and after timber harvesting activities in two treatment watersheds in the Stuart–Takla region. Year and starting date of the event are noted with its duration in days provided in parentheses. The actual discharges (solid line) are compared with estimates of discharges had harvesting not occurred using an unharvested control (broken line). Prediction limits (grey line) (95%) about the estimated values were included to assist in the evaluation of the postharvest effects. Note the differences in discharge scale between B3 and B5. Missing 1997 B5 data resulted from datalogger failure.



B3 watershed (Story et al. 2003), suggesting that snowmelt could provide a greater contribution to peak flow in B5 than in B3.

The large amount of riparian retention in the B3 watershed was unlikely to be the primary factor responsible for the depressed peak flow response relative to B5. Although the variable source area concept suggests that forestry activities within the riparian area will have a disproportionately

high influence on freshet hydrology relative to activities in the rest of the watershed (Hewlett and Hibbert 1967), more recent research suggests that the proportion of peak flow attributed to overland flow from riparian areas to headwater systems becomes trivial as the regolith becomes saturated (Sidle et al. 2000). However, it is reasonable to speculate that the compacted road surfaces (i.e., two stream crossings and log landing adjacent to B5) provided conduits for over-

Fig. 4. Average daily total suspended sediment concentrations (TSS) (mg/L) during the snowmelt freshet period before (1996) and after timber harvesting activities in two treatment watersheds in the Stuart–Takla region. Year and starting date of the event are noted with its duration in days provided in parentheses. The actual TSS concentrations (solid line) are compared with estimates of TSS had harvesting not occurred using an unharvested control (broken line). Prediction limits (grey line) (95%) about the estimated values were included to assist in the evaluation of the postharvest effects. Note the differences in TSS scale between B3 and B5.

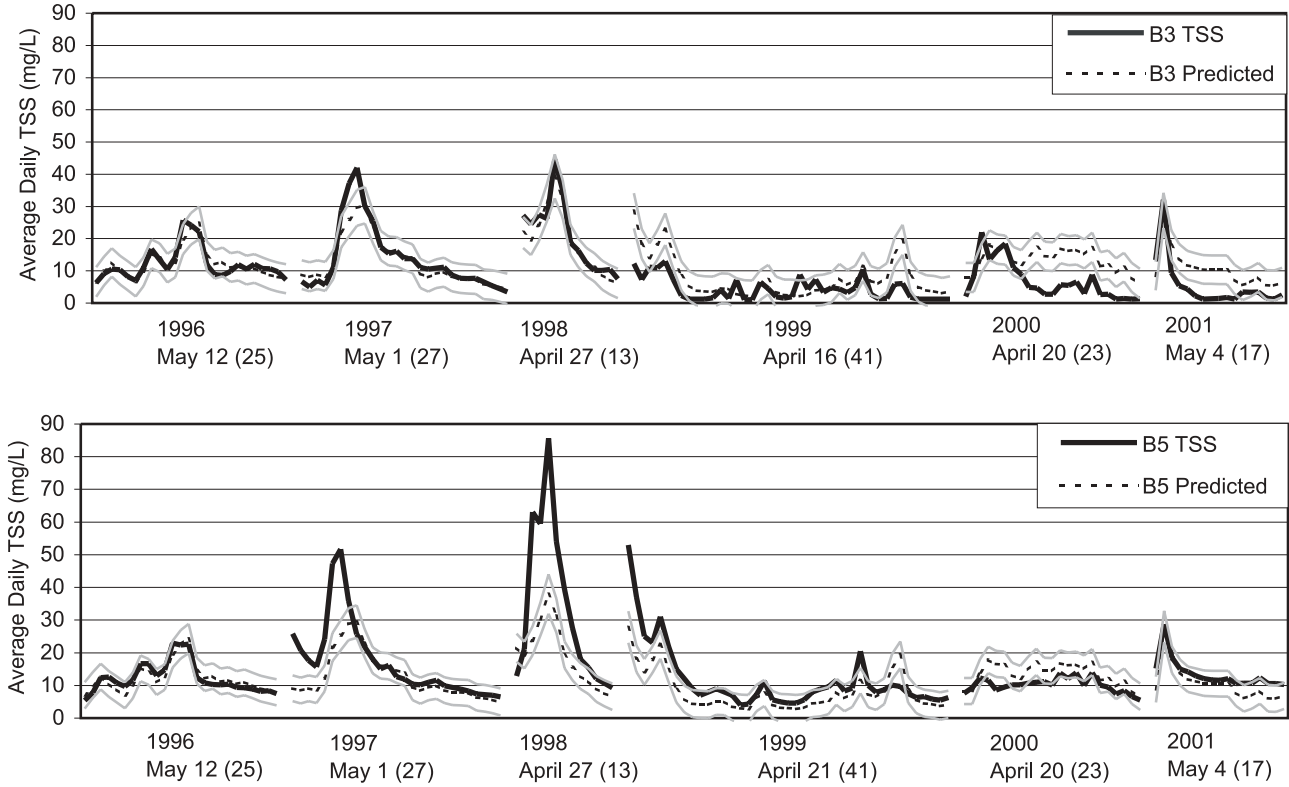


Fig. 5. Decline in snowpack water equivalency in the spring of each year. Samples were taken from a road right-of-way clearing near the upper boundary of the B5 cutblock. The largest snowpack occurred in 1997, the smallest in 1998.

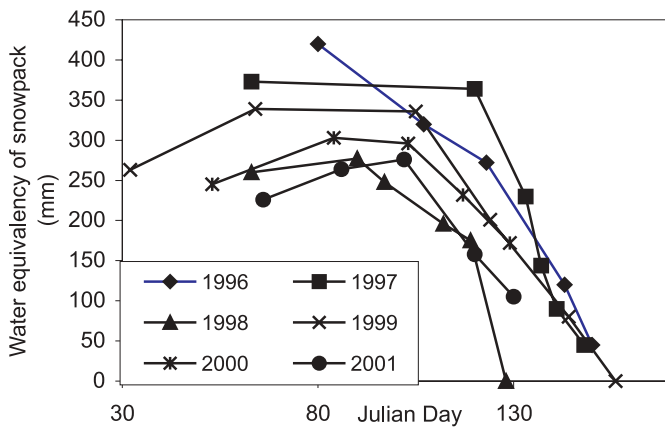
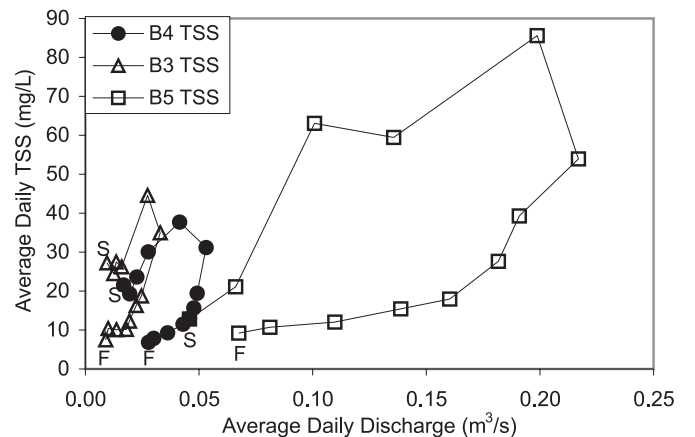


Fig. 6. Sediment output during the rising and falling limbs of the snowmelt hydrograph in the three experimental streams to provide an example of event hysteresis in 1998. S, the beginning of an event; F, the end of an event; TSS, total suspended sediment.



land flow not present in the B3 watershed and contributed to increased peak flow runoff.

Recently, resource managers have emphasized the importance of hydrologic recovery as a land-use planning tool (Ziemer and Lisle 1998), and yet increased snowmelt accumulation and peak flow following forest harvesting may persist for a considerable time. In the Fraser Experimental Forest in Colorado, water yield increased with snowpack

water equivalency and melt period and decreased with time, but recovery to preharvest levels was predicted to take 90 years (Troendle and King 1985). Hudson (2000) reported recovery of snow accumulation and melt processes in coastal montane areas taking decades. Variable retention and other harvesting approaches that minimize impact to shrubs and noncommercial trees and maximize opportunities for

regrowth will allow transpiration processes to recover quickly (5 years on the coast, Ziemer and Lisle 1998). However, full canopy regrowth and the recovery of natural rainfall interception and snowpack processes occur more slowly particularly in northern boreal and sub-boreal settings and (or) at higher elevations (Beschta et al. 1987). Lack of apparent hydrological recovery after 5 years in our study is not surprising despite the retention of understory riparian vegetation and the presence of relatively few roads.

Total suspended sediment concentrations are often larger during the rising limb of the storm hydrographs in coastal watersheds and decline at equivalent discharge with seasonal progression (e.g., Paustian and Beschta 1979). In interior British Columbia sub-boreal settings, sediments stored on hillslopes and in the channel through the winter low-flow period are most likely to be mobilized as water levels rise during the first large snowmelt event in the spring (Cheong et al. 1995). The hysteresis in our study streams are described as type 2A curves (Fig. 6) caused by a depletion of sediment during the early runoff period as a result of small supply or an intense initial event (Williams 1989). The glacier deposits that are the primary sediment supply for many streams are less prevalent in small upland watersheds typified by this study than in valley bottoms (Jordan 2001).

Several studies have reported an increase in suspended sediment following forest operations, particularly during storm events or during the spring snowmelt period (Leaf 1970; Everest et al. 1987; Brownlee et al. 1988; Ryan 1991). Following forestry operations, increased stream power can destabilize woody debris or be redirected by discarded logging slash, releasing stored sediment, increasing bank erosion, and increasing the overall sediment supply during spring freshet. These processes are exacerbated if falling and yarding and (or) channel-crossing activities actually take place in the channel or on the active floodplain.

A harvesting prescription that retains a large portion of the riparian vegetation and requires all operations to be located well back from the active channel (e.g., 5-m machine-free zone) uncouples forest harvesting activities from some stream channel processes and is less likely to create large sources of sediment. As a result of this and the absence of stream crossings in the high-retention cutblock (B3), TSS concentration rarely exceeded levels predicted from pre-harvesting data. In general, when smaller portions of the riparian forest are retained (e.g., B5), a greater opportunity exists for channel disturbance and increased sediment supply from in-stream and riparian sources (Dykstra and Froehlich 1976; Steinblums et al. 1984). However, this hypothesis may be too simplistic. Riparian leave strips have been shown to be ineffective protection when point sources such as roads transport sediment to the stream (Slaney et al. 1977). Observations of sediment sources from creek walks along the length of B5 identified the major sources of sediment as a stream crossing and a nearby log landing. Other significant point sources of sediment were not found along the entire channel of either stream, despite substantial riparian wind-throw following harvesting, particularly in B3 (Macdonald et al. 2003), nor was there any obvious evidence of channel instability (e.g., channel and (or) bank erosion or woody debris redistribution). Christie and Fletcher (1999) traced multi-element geochemical anomalies in stream sediments to

stream crossing and ditch sources in these watersheds. In 1997, the snowmelt runoff from the B5 landing carried large amounts of surface sediment via the road surface to the creek crossing. In the fall of 1997, after the culvert at this crossing was removed and no erosion control measures were taken to reduce sediment delivery, TSS exceeded predicted levels for 3 years, particularly in 1998.

Several studies concluded that road construction and use contribute disproportionately to the sediment supply and delivery to streams, at least in coastal settings (Brown and Krygier 1971; Reid and Dunne 1984; Everest et al. 1987). Working in the southeast interior of British Columbia, Jordan (2001) concluded that road surfaces provided the most important source of development-related sediment, and sediment yield was lowest in watersheds with granitic-based bedrock geology. However, Henderson and Toews (2001), working in the same area, suggest that sediment from natural sources greatly exceeded that produced from roads. The interior watersheds typified by this study, while perhaps less susceptible to mass wasting and road runoff events than those in steeper and wetter ecosystems on the coast, frequently have soils originating from fine glaciolacustrine deposits that can increase site sensitivity (Beaudry 1998b). Based on this study, we concluded that machine-free zones and both of our riparian treatments will provide adequate protection to the stream channel from direct physical bank disturbance. Assuming the use of readily available remedies, sediment transport from the hillslopes to the stream channel via roads and ditches can also be minimized. Even without these remedies, we found that TSS impacts recovered on a shorter time scale than hydrological impacts as the channel and access roads-trails stabilized following harvesting. Other studies have also noted a rapid decline in the impact of roads following their construction, particularly when usage declines or ceases (Reid and Dunne 1984; Henderson and Toews 2001). This finding is in opposition to the suggestion that sediment recovery is linked to hydrological recovery in Caspar Creek (Lewis et al. 2001), a link that assumes that channel configuration affects sediment loads to a greater degree than delivery from hillslopes. Stored sediments in channels, particularly the lower gradient, coarse-textured reaches, will be released according to hydraulic energy regimes, not supply from adjacent riparian areas, and will take several years to move downstream. Sediment loads in high gradient headwater tributaries may depend to a great degree on supply from reach-scale point sources that are accessed by specific activities, not in association with general channel or upslope disturbance at a watershed scale. Others have found that BMPs applied to forestry and other land-use activities can prevent unacceptable changes to sediment loads and other forms of pollution in streams (Binkley and Brown 1993; Welch et al. 1998).

There is a concern that increased streamflow and higher concentrations of TSS can reduce fish habitat complexity and eliminate key features. Channel scour, gravel removal, sediment infiltration, turbidity, and the redistribution of woody debris can occur at frequencies and magnitudes beyond natural regimes and exceed the resiliency of aquatic communities (Lake 2000; Reice et al. 1990). Suspended sediment loads in our study streams increased, occasionally in concentrations that exceeded regulatory guidelines, includ-

ing European Inland Fisheries Advisory Commission (1964), Canadian Council of Resource and Environmental Ministers (1987), and the Canadian Council of Ministers of the Environment guidelines, that are based on Caux et al. (1997). When exposed to 100 mg/L or less, several salmonid species demonstrate impaired feeding and growth (McLeay et al. 1987), sublethal stress responses (Servizi and Martens 1992) and potential distribution to habitats with lower sediment levels if available (Sigler et al. 1984; McLeay et al. 1987; Scrivener et al. 1994). The degree of impact is dependent on the exposure duration as well as the TSS concentration (Newcombe and MacDonald 1991). During this investigation, all events that produced TSS concentrations approaching 100 mg/L were of short duration (<24 h) and infrequent (e.g., B5 in 1998).

Conclusion

Our challenge in the face of resource development pressures in small headwater catchments is to maintain water quality and natural hydrologic patterns so as to protect local values and downstream resources. In addition to being habitat for fish and macroinvertebrates and providing a source of domestic water (Jordan 2001), small streams are important export sites that provide water, sediment, nutrients, and biota to downstream sites (Wipfli and Gregovich 2002). Our research found an increase in peak flow and mean daily freshet discharge following harvesting, particularly in B5. A delay in the impact until the second postharvest freshet was attributed to an interaction among winter harvest timing, snowmelt, and freshet flow generation characteristics. There was no sign of a hydrologic recovery in the 5-year postharvest period. Flow-related changes persisted beyond the project's 5-year postharvest sample collection period and were likely associated with both vegetation loss and road construction. Increased TSS was detected during the snowmelt freshet following harvest, most notably in B5 where the primary source of sediment was traced to a log landing and stream crossing. Less than 2 years following the deactivation of the road and crossing site, sediment levels were at or below preharvest levels. The riparian treatments were effective at protecting stream banks from physical damage, but disruptions to the channel from windthrow in the high-retention watershed may eventually contribute to the sediment supply. BMPs for forestry operations near small streams must minimize physical disturbance to the channel, particularly in regard to stream crossings, road drainage patterns, road maintenance, and road deactivation.

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References

- Adams, P.W., Flint, A.L., and Fredriksen, R.L. 1991. Long-term patterns in soil moisture and revegetation after a clearcut of a Douglas-fir forest in Oregon. *For. Ecol. Manage.* **41**: 249–263.
- Bates, C.G., and Henry, A.J. 1928. Forest and streamflow experiment at Wagon Wheel Gap, Colorado. *Mon. Weather Rev.* **30**(Suppl.): 1–79.
- Beaudry, P.G. 1998a. Effects of forest harvesting on streamflow and sediment concentrations of small streams in central British Columbia. *In Mountains to Sea: Human Interactions with the Hydrologic Cycle*, 10–12 June 1998, Proceedings of the 51st Annual Conference of the Canadian Water Resources Association, Victoria, B.C. *Edited by Y. Alila*. Canadian Water Resources Association, Cambridge, Ont. pp. 80–89.
- Beaudry, P.G. 1998b. Suspended sediment regimes in three experimental watersheds in the Takla area of north-central British Columbia. *In Forest–Fish Conference: Land Management Practices Affecting Aquatic Ecosystems*, 1–4 May 1996, Calgary, Alta. *Technical coordinators: M.K. Brewin and D.M.A. Monita*. Can. For. Serv. Inf. Rep. NOR-X-356. pp. 231–240.
- Beaudry, P.G., and Golding, D.L. 1987. Snowmelt and runoff during rain-on-snow in forest and adjacent clearcut. *In Proceedings of the Snow Property Measurement Workshop*, 1–3 April 1985, Lake Louise, Alta. *Compiled by P.R. Kry*. National Research Council, Associate Committee on Geotechnical Research, Ottawa, Ont. Tech. Mem. 140. pp. 285–313.
- Berris, S.N., and Harr, R.D. 1987. Comparative snow accumulation and melt during rainfall in forested and clear-cut plots in the western Cascades of Oregon. *Water Resour. Res.* **23**: 135–142.
- Beschta, R.L., Bilby, R.E., Brown, G.W., Holtby, L.B., and Hofstra, T.D. 1987. Stream temperature and aquatic habitat: fisheries and forestry interactions. *In Streamside Management: Forestry and Fisheries Interactions*, 12–14 February 1986, University of Washington, Institute of Forest Resources, Seattle, Wash. *Edited by T.W. Cundy and E.O. Salo*. Institute of Forest Resources, University of Washington, Seattle, Wash. pp. 191–232.
- Binkley, D., and Brown, T.C. 1993. Forest sources as non-point sources of pollution in North America. *Water Resour. Bull.* **29**: 729–740.
- British Columbia Ministry of Forests. 1995. Riparian area management guidebook. Co-published by B.C. Ministry of Environment, Victoria, B.C.
- Brosfoske, K.D., Chen, J., Naiman, R.J., Franklin, J.R. 1997. Harvesting effects on microclimatic gradients from small streams to uplands in western Washington. *Ecol. Appl.* **7**: 1188–1200.
- Brown, G.W., and Krygier, J.T. 1971. Clear-cut logging and sediment production in the Oregon Coast Range. *Water Resour. Res.* **7**: 1189–1198.
- Brownlee, M.J., Shepherd, B.G., and Bustard, D.R. 1988. Some effects of forest harvesting on water quality in the Slim Creek watershed in the central interior of British Columbia. *Can. Tech. Rep. Fish. Aquat. Sci.* **1613**.
- Canadian Council of Resource and Environmental Ministers. 1987. Total suspended solids. *In Canadian environmental guidelines*. Environment Canada, Ottawa, Ont.
- Caux, P.Y., Moore, D.R., and MacDonald, D. 1997. Ambient water quality guidelines (criteria) for turbidity, suspended sediment, and benthic sediments technical appendix. B.C. Ministry of En-

- vironment, Lands and Parks, Water Quality Branch, Victoria, B.C.
- Cheong, A.L., Scrivener, J.C., Macdonald, J.S., Andersen, B.C., and Choromanski, E.M. 1995. A discussion of suspended sediment in the Takla Lake region: the influence of water discharge and spawning salmon. *Can. Tech. Rep. Fish. Aquat. Sci.* **2074**.
- Christie, T., and Fletcher, W.K. 1999. Contamination from forestry activities: implications for stream sediment exploration programmes. *J. Geochem. Explor.* **67**(1): 201–210.
- Church, M. 1995. Fine sediments in small streams in coastal British Columbia: a review of research findings. *In* Carnation Creek and Queen Charlotte Islands Fish/Forestry Workshop: Applying 20 Years of Coast Research to Management Solutions, 1994, Queen Charlotte City, B.C. *Edited by* D.L. Hogan, P.J. Tschaplinski, and S. Chatwin. B.C. Ministry of Forests, Research Branch, Victoria, B.C. Land Manage. Handb. 41. pp. 119–133.
- Church, M., Kellerhals, R., and Day, T.J. 1989. Regional clastic sediment yield in British Columbia. *Can. J. Earth Sci.* **26**: 31–45.
- Collett, A., and Ryder, J.M. 1997. Baptiste Creek Watershed: detailed terrain and sediment source mapping with interpretations for slope stability, erosion potential and sediment transfer. J.M. Ryder and Associates Terrain Analysis Inc., Vancouver, B.C.
- Dykstra, D.P., and Froehlich, H.A. 1976. Cost of stream protection during timber harvest. *J. For.* **74**: 684–687.
- European Inland Fisheries Advisory Commission. 1964. Water quality criteria for European freshwater fish. Food and Agriculture Organization of the United Nations, Rome. EIFAC/1.
- Everest, F.H., Beschta, R.L., Scrivener, J.C., Koski, K.V., Sedell, J.R., and Cederholm, C.J. 1987. Fine sediment and salmon production: a paradox. *In* Streamside Management: Forestry and Fisheries Interactions, 12–14 February 1986, University of Washington Institute of Forest Resources, Seattle, Wash. *Edited by* T.W. Cundy and E.O. Salo. Institute of Forest Resources, University of Washington, Seattle, Wash. pp. 98–142.
- Gilliam, J.W. 1994. Riparian wetlands and water quality. *J. Environ. Qual.* **23**: 896–900.
- Gregory, S.V., Swanson, F.J., McKee, W.A., and Cummings, K.W. 1991. An ecosystem perspective of riparian zones. *Bioscience*, **41**: 540–550.
- Hartman, G.F., and Scrivener, J.C. 1990. Impacts of forestry practices on a coastal stream ecosystem, Carnation Creek, British Columbia. *Can. Bull. Fish. Aquat. Sci.* **223**.
- Heinonen, J. *In press*. Snow survey measurements in the Stuart–Takla project. *In* Forestry impacts on fish habitat in the northern interior of British Columbia: a compendium of research from the Stuart–Takla fish forestry interaction study. *Edited by* E.A. MacIsaac. *Can. Tech. Rep. Fish. Aquat. Sci.*
- Henderson, G.S., and Toews, D.A.A. 2001. Using sediment budgets to test the watershed assessment procedure in southeastern British Columbia. *In* Watershed assessment in the southern interior of British Columbia. *Edited by* D.A.A. Toews and S. Chatwin. B.C. Ministry of Forests, Research Branch, Victoria, B.C. Work. Pap. 57. pp. 189–208.
- Hewlett, J.D., and Hibbert, A.R. 1967. Factors affecting the response of small watersheds to precipitation in humid areas. *In* Forest hydrology. *Edited by* W.E. Sopper and H.L. Lull. Pergamon Press Inc., New York. pp. 275–290.
- Hicks, B.J., Beschta, R.L., and Harr, R.D. 1991. Long-term changes in streamflow following logging in western Oregon and associated fisheries implications. *Water Resour. Bull.* **27**: 217–226.
- Hornbeck, J.W., Adams, M.B., Corbett, E.S., Verry, E.S., and Lynch, J.A. 1993. Long-term impacts of forest treatments on water yield: a summary for northeastern U.S.A. *J. Hydrol.* **150**: 323–344.
- Hudson, R. 2000. Snowpack recovery in regenerated coastal British Columbia clearcuts. *Can. J. For. Res.* **30**: 548–556.
- Hudson, R. 2001. Storm-based sediment budgets in a partially harvested watershed in coastal British Columbia. B.C. Ministry of Forests, Victoria, B.C. Tech. Rep. TR-009.
- Hutchinson, D.G., and Moore, R.D. 2000. Throughflow variability on a forested hillslope underlain by compacted glacial till. *Hydrol. Processes*, **14**: 1751–1756.
- Jordan, P. 2001. Sediment budgets in the Nelson Forest Region. B.C. Ministry of Forests, Research Branch, Victoria, B.C. Work. Pap. 57. pp. 174–188.
- Lake, P.S. 2000. Disturbance, patchiness, and diversity in streams. *J. North Am. Benthol. Soc.* **19**: 573–592.
- Leaf, C.F. 1970. Sediment yields from the Colorado snow zone. *J. Hydraul. Div. Am. Soc. Civ. Eng.* **96** HY-1. pp. 87–93.
- Lewis, J., Mori, S.R., Keppeler, E.T., and Ziemer, R.R. 2001. Impacts of logging on storm peak flows, flow volumes and suspended sediment loads in Caspar Creek, California. *In* Land use and watersheds: human influence on hydrology and geomorphology in urban forest areas. *Edited by* M.S. Wigmosta and S.J. Burgess. American Geophysical Union, Washington, D.C. pp. 85–126.
- Luce, C.H., and Cundy, T.W. 1994. Parameter identification for a runoff model for forest roads. *Water Resour. Res.* **30**: 1057–1069.
- Macdonald, J.S., Scrivener, J.C., and Smith, G. 1992. The Stuart–Takla Fisheries/Forestry Interaction Project: study description and design. *Can. Tech. Rep. Fish. Aquat. Sci.* **1899**.
- Macdonald, J.S., MacIsaac, E.A., and Herunter, H. 2003. The effects of variable-retention riparian buffer zones on water temperatures in small headwater streams in sub-boreal forest ecosystems of British Columbia. *Can. J. For. Res.* **33**: 1371–1382.
- McLeay, D.J., Birtwell, I.K., Hartman, G.F., and Ennis, G.L. 1987. Responses of Arctic grayling (*Thymallus arcticus*) to acute and prolonged exposure to Yukon placer mining sediment. *Can. J. Fish. Aquat. Sci.* **44**: 658–673.
- Newcombe, C.P., and MacDonald, D.D. 1991. Effects of suspended sediment on aquatic ecosystems. *N. Am. J. Fish. Manage.* **11**: 72–82.
- Parshall, R.L. 1936. The Parshall measuring flume. Colorado State College, Colorado Experiment Station, Fort Collins, Colo. Bull. 423(March).
- Paustian, S.J., and Beschta, R.L. 1979. The suspended sediment regime of an Oregon coast range stream. *Water Resour. Bull.* **15**: 144–154.
- Reice, S.R., Wissmar, R.C., and Naiman, R.J. 1990. Disturbance regimes, resilience and recovery of animal communities and habitats in lotic ecosystems. *Environ. Manage.* **14**: 647–659.
- Reid, L.M., and Dunne, T. 1984. Sediment produced from forest road surfaces. *Water Resour. Res.* **20**(11): 1753–1761.
- Ryan, P.A. 1991. Environmental effects of sediment on New Zealand streams: a review. *N. Z. J. Mar. Freshw. Res.* **25**: 207–221.
- Scrivener, J.C., Brown, T.G., and Anderson, B.C. 1994. Juvenile chinook salmon (*Oncorhynchus tshawytscha*) utilization of Hawks Creek, a small non-natal tributary of the upper Fraser River. *Can. J. Fish. Aquat. Sci.* **51**: 1139–1146.
- Servizi, J.A., and Martens, D.W. 1992. Sublethal responses of coho salmon (*Oncorhynchus kisutch*) to suspended sediment. *Can. J. Fish. Aquat. Sci.* **49**: 1389–1395.
- Sidle, R.C., Tsuboyama, Y., Noguchi, S., Hosoda, I., Fujieda, M., and Shimizu, T. 2000. Stormflow generation in steep forested

- headwaters: a linked hydrogeomorphic paradigm. *Hydrol. Process.* **14**: 369–385.
- Sigler, J.W., Bjornn, T.C., and Everest, F.H. 1984. Effect of chronic turbidity on density and growth of steelhead and coho salmon. *Trans. Am. Fish. Soc.* **113**: 142–150.
- Slaney, P.A., Halsey, T.G., and Tautz, A.F. 1977. Effects of forest harvesting practices on spawning habitat of stream salmonids in the Centennial Creek watershed, British Columbia. B.C. Ministry of Recreation and Conservation, Victoria, B.C. Fish. Manage. Rep. 73. pp. 45.
- Sokal, R.R., and Rohlf, F.J. 2000. *Biometry: the principles and practice of statistics in biological research*, 3rd ed. W.H. Freeman and Company, New York.
- Spittlehouse, D.L. 1998. Rainfall interception in young and mature conifer forests in British Columbia. *In* Proceedings of the 23rd Conference on Agricultural and Forest Meteorology, 2–6 November 1998, Albuquerque, N.M. American Meteorological Society, Boston, Mass. pp. 171–174.
- Steinblums, I., Froehlich, H.A., and Lyons, J.K. 1984. Designing stable buffer strips for stream protection. *J. For.* **82**: 49–52.
- Story, A., Moore, R.D., and Macdonald, J.S. 2003. Stream temperatures in two shaded reaches below cutblocks and logging roads: downstream cooling linked to subsurface hydrology. *Can. J. For. Res.* **33**: 1383–1396.
- Troendle, C.A., and King, R.M. 1985. The effect of timber harvest on Fool Creek watershed, 30 years later. *Water Resour. Res.* **21**: 1915–1922.
- Troendle, C.A., and King, R.M. 1987. The effect of partial and clearcutting on streamflow at Deadhorse Creek, Colorado. *J. Hydrol.* **90**: 145–157.
- Van Haveren, B.P. 1988. A re-evaluation of the Wagon Wheel Gap forest watershed experiment. *For. Sci.* **34**: 208–214.
- Verry, E.S., Lewis, J.R., and Brooks, K.N. 1983. Aspen clearcutting increases snowmelt and storm flow peaks in north central Minnesota. *Water Resour. Bull.* **19**(1): 59–67.
- Welch, E.B., Jacoby, J.M., and May, C.W. 1998. Stream quality. *In* River ecology and management: lessons from the Pacific coastal ecoregion. *Edited by* R.J. Naiman and R.E. Bilby. Springer-Verlag New York Inc., New York. pp. 69–85.
- Williams, G.P. 1989. Sediment concentration versus water discharge during single hydrological events in rivers. *J. Hydrol.* **111**: 89–106.
- Wipfli, M.S., and Gregovich, D.P. 2002. Export of invertebrates and detritus from fishless headwater streams in southeast Alaska: implications for downstream salmonid production. *Freshw. Biol.* **47**: 957–969.
- Young, K.A. 2000. Riparian zone management in the Pacific Northwest: Who's cutting what? *Environ. Manage.* **26**(2): 131–144.
- Ziemer, R.R., and Lisle, T.E. 1998. Hydrology. *In* River ecology and management: lessons from the Pacific coastal ecoregion. *Edited by* R.J. Naiman and R.E. Bilby. Springer-Verlag New York Inc., New York. pp. 43–62.