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Modelling changes in suspended sediment from forest road surfaces in a coastal watershed of British Columbia

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Abstract:

Erosion from logging road surfaces, cut slopes, banks, and ditches represents a chronic source of sediment input to streams that can degrade aquatic habitats. Road surface erosion is of particular concern because the magnitude of sediment generation when traffic levels are high can be large. Current models for predicting sediment production from roads require information on area-specific sediment delivery, which is not often available. Here, we developed a model to quantify suspended sediment concentrations (SSC) generated by forest roads surfaces under different conditions of use and density. This model is designed for a typical medium-size coastal watershed of British Columbia or the American Pacific Northwest, and was applied to the Chilliwack River watershed as a case study. The results illustrate that intensive use of forest roads combined with high road density can increase the number of extreme sedimentation events over a predetermined threshold. A comparison of the effects of road density and the level of road use suggests that the level of road use is more important than the road density for the generation of fine sediment from road surfaces. However, the model omits the impact of roads on mass movements in a watershed, which represent a major source of sediment in steep watersheds, so the effect of road density is likely more substantial than the model predicts. The model is an attempt to overcome field data limitations by using an empirical relation between SSC and traffic variables, and presents a starting point for more intensive field studies that could be used to validate it. Copyright © 2013 John Wiley & Sons, Ltd.

KEY WORDS sediment yield; forest road traffic levels; number of sediment events; road sediment generation model

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INTRODUCTION

Forest roads are an important component of timber extraction, mining, fishing, and other commercial and recreational activities. However, roads have well-known negative impacts on the aquatic environment and are thought to produce more sediment than most other forestry activities (Beschta, 1978; Reid and Dunne, 1984; Meehan, 1991; Gucinski *et al*., 2001; Hassan *et al*., 2005; Hudson, 2006). Roads can also change basin terrain stability and hydrology with consequent downstream effects and can directly alter riparian and stream habitat characteristics (Naiman *et al*., 1992; Gucinski *et al*., 2001). Ecological effects of roads are of increasing concern for watershed management and conservation as the number of road-free wilderness areas decline.

Forest roads change the hydrology of watersheds by intercepting rainfall directly on their surfaces and banks (Luce and Cundy, 1994; Ziegler and Giambelluca, 1997) and by modifying the runoff corridors by which water flows to the stream channel (Moore and Wondzell, 2005). The removal of forests for construction of road surfaces and their right-of-ways contributes to increased snow accumulation and changes the timing and rate of snowmelt and evapotranspiration, which can change the watershed's hydrological regime (Jones, 2000). Peak flow responses to forestry activities are highly variable and depend on many factors such as basin size, aspect, elevation, soils, and soil moisture storage (Jones and Grant, 1996). Road-related variables, such as the overall road density or building on unstable soils, contribute to a high probability (50–75%) of observing changes in peak flows and impact the suspended sediment yield (McFarlane, 2001). Also, roads can intercept sub-surface groundwater that normally moves down the hillslope; this accelerated movement of water contributes to increased

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frequencies of extreme flow events (Megahan and Clayton, 1983; Wemple *et al*., 1996).

In steep watersheds, mass movement events caused by road construction activities, such as hillslope oversteepening, overloading, support removal, and concentrating surface runoff, can also be important sediment contributors (Sidle and Ochiai, 2006; MacDonald and Coe, 2007). Although, Sidle and Ochiai (2006) suggested that an increase in the mass movement due to forest roads is likely the result of changes in the hydrological regime rather than of construction activities, forest roads can cause a 10 to 300-fold increase in mass movement erosion rates, and the proportion of sediment entering streams is generally high for road-induced failures (e.g. Sidle and Ochiai, 2006; MacDonald and Coe, 2007). In north-western North America, the increase in the sediment production rate due to forest road ranges between 20 and 340 times the natural rate (see Sidle and Ochiai, 2006, their Table 6.1). The large pulse of sediment from mass movement can alter the channel morphology, bed composition, and channel habitat.

Road surface erosion, including erosion from cut slopes, banks, and ditches, can also represent significant sources of chronic sediment input to streams (Beschta, 1978; Reid and Dunne, 1984; Meehan, 1991; Naiman *et al*., 1992; Luce and Black, 1999). This is of particular concern because of the fine texture (usually <2 mm) of the material produced (e.g. Ramos-Scharron and MacDonald, 2005) and the chronic nature of the sediment delivery into streams. Roads can increase surface erosion by two to three orders of magnitude causing chronic impacts on stream ecosystems (see MacDonald and Coe, 2007, their Table 1). Reid and Dunne (1984) asserted that traffic is the dominant factor controlling sediment production from road surfaces. Heavily used roads contribute 130 times more material than abandoned roads. Luce and Black (1999) found that contributing segment area and road material are the key controlling factors for road surface-related sediment productions. For example, on average, soil-surface roads contributed 25 times more sediment than gravel paved roads (Sheridan and Noske, 2007).

The relative importance of road surfaces and road-related mass movement erosional processes depends on a wide range of variables and the interaction among them. The type and the magnitude of the process depend on the characteristics of the watershed (e.g. geology, climate, and physiography), the road type (e.g. design, construction and maintenance, location relative to the stream network and crossing), and traffic (e.g. density and type) (Reid and Dunne, 1984; Jones, 2000; Madej, 2001; Wemple *et al*., 2001; MacDonald and Coe, 2007). Reid (1981) reported that road-induced landslides produce 60% of the road-related sediment, while 20% of this sediment comes from road surfaces. In terms of suspended sediment production, they reported that landslides and surfaces were equal. Higher turbidity levels have been detected below stream crossings compared to above stream crossings (e.g. Bilby, 1985). For example, Lane and Sheridan (2002) reported that during rainfall events, suspended sediment load was 3.5 times higher below a crossing than above. Overall, road surfaces were found to contribute about 30% of the total fine sediment load in streams in the UK (Gruszowski *et al*., 2003). Lower values were reported by Sheridan and Noske (2007): between 3% and 6% of the total annual load are road related.

A portion of the sediment produced by forest roads ends up in rivers and streams increasing the number of high suspended sediment concentration (SSC) events causing the degradation of aquatic habitats. The amount of sediment delivered to rivers and streams from road construction and use has been an active field of research in north-western North America for the past 50 years (see reviews by Kerr, 1995 and Gucinski *et al*., 2001). It is difficult to quantify road-related sediment flux because of watershed specific conditions (e.g. terrain, soils, climate, and geomorphology), study duration, and the quality of data (Ashmore *et al*., 2000). In spite of the large number of studies on the topic, few (see references below) have used simulation to quantify sediment flux in a river in response to changing road management and conditions such as density and use within the watershed.

Applying hydrologic and sediment models to support forest management and decision making has been the objective of several studies (e.g. Alila and Beckers, 2001; Borga *et al*., 2004). The Water Erosion Prediction Project (WEPP) with its extended prototype the Cross Drain Spacing and Sediment Yield Program (X-DRAIN) is a process-based model that estimates the amount of sediment generated by forest roads (Annual Sediment Yield- ASY) based on climate, soil type, gravel addition, topography, and vegetation cover (Elliot *et al*., 1999a,b). The Road Sediment Delivery Model (SEDMODL2) has been used to calculate the ASY using a data-driven spatial framework that includes topography, road surface condition, traffic level, surface area, road gradient, and annual rainfall (Dubé and McCalmon, 2004; Welsh, 2008). Although these models can help evaluate the potential effects of forestry activities on forest hydrology and sediment generation, they require extensive data that often do not exist for many watersheds.

Given the complexity of quantifying the responses of SSC and discharge (Q) to changing road conditions, a simplified data-driven simulation approach with few parameters that include both theoretical considerations of watershed hydrology and sediment production from road surfaces can help to explore the potential impact of road-related factors on the watershed's sediment regime. The main purpose of this study is to provide a model to quantify the daily SSC generated by forest road surfaces under different conditions of road use and density in a generic medium-sized coastal watershed of British Columbia. The focus of this model is on sediment production from road surface erosion rather than road-induced mass-movement, which is a significant source of sediment to streams. However, road surface erosion presents a relatively predictable, chronic source of sediment to streams, and its effects can extend for long periods. Additionally, little field data exists by which this model can be calibrated, thereby limiting this model to be more a theoretical framework than a precise predictive tool.

MODEL DEVELOPMENT

We developed the model based on a sediment budget study conducted by Metro Vancouver (GVRD, 1999), which used the results from Reid (1981) to estimate the annual fine sediment yield (AFSY) from forest road surfaces in three managed coastal watersheds (Seymour, Capilano, and Coquitlam). A comparison between GVRD (1999) and similar studies is presented in Table I. Our model estimates potential changes in the AFSY for different conditions of road use and density with respect to a baseline scenario of the current road status and use conditions, and it is intended for use at the watershed scale. After defining the baseline scenario, the model uses the total sediment yield, which is derived directly from daily hydrological and SSC time series data, to discriminate between road surface-generated and non-road surface-generated SSC. Last, the model simulates changes in the time series of road surface-generated daily SSC for any given forest management scenario by introducing potential changes in peak discharge and volume of suspended sediments transported, specific to each scenario.

Estimating the AFSY from forest roads

First, we estimated the AFSY, the amount of fine sediment (<63 μm) exported by the river in a year exclusively from road-related factors, working under the assumptions that the physiographic and road parameters in the watershed remain constant (i.e. number of road segments, stream crossings, slope of the road, slope of the terrain, and number of streams), and the only variable factor is road use. To describe variations in road use, we employed the definitions of Reid (1981): Light, use only by light vehicles; Moderate, use by fewer than four logging trucks per day; and Heavy, use by more than four logging trucks per day. Prior to estimating the AFSY, it is necessary to obtain the slope and lengths of road segments for the entire study area. Estimation of the AFSY follows the relation (GVRD, 1999):

$$AFSY_i = l_i u_i (LR_i)(DR_i) \qquad (1)$$

where AFSY_i is the annual fine sediment yield (tonnes yr^{-1}) for a given road network (i). The length of the road network

Table I. Comparison among similar studies of road delivery in north-western North America watersheds

Study	Location	Inputs for estimating AFSY	Area watershed (ha)	Road (km)	AFSY (tonnes/km/year
This paper	BC	Road slope, number of stream reaches and gullies, and road use	123 000	541.2	Light use - 3.67 Moderate use - 41.04
GVRD, 1999	BC	Road slope, number of stream reaches and gullies, and road use	19 328	118.7	Light use - 3.14
Luce and Black (1999)	Oregon	Soil type, segment length, road slope, cut-slope height, time since construction, degree of rutting, inslope/crown/outslope, aspect, cut-slope, slope position, road width, rainfall, forest cover, surfacing, and road use	Unspecified	Ranged from 0.04 to 0.110	Light use - ranged from 0.1 to 1.8 tonnes
Reid and Dunne (1984)	Washington	Road use and road length	2000	2.5 km/km^2	Light use - 3.8 Moderate use - 42 Heavy use - 500

(l_i) is measured in kilometers; u_i is the sediment yield in tonnes yr^{-1} km^{-1} (Table II), based on the road network's use and slope; LR_i is the loss ratio (Table II), and DR_i is the delivery ratio (Table III). The loss ratio reflects diversions of sediment-laden water by waterbars or road crowning, which then percolates into soils and thereby deposits its sediment. The loss ratio was determined by GVRD (1999), as a function of road slope, and found to decrease with it. The delivery ratio reflects the connectivity between the road prism and the stream network and is the percentage of sediments that end up in the stream for a given terrain slope and number of major and ephemeral streams in the watershed (Table III). Delivery ratios were estimated by GVRD (1999) using existing watershed polygon data sets that detailed the terrain slope and the presence or absence of major and ephemeral streams. The difference between the loss ratio and the delivery ratio is the former reflects a loss of sediment without obvious storage and the latter reflects sediment stored on hillslopes, trapped by vegetation, deposited on floodplains or in pools and swamps.

The total suspended sediment yield generated exclusively by roads for the entire time series is estimated by multiplying $AFSY_i$ times the number of years in the time series of available data (y), expressed in tonnes. The total suspended sediment yield is estimated under the assumption that road use does not change over time.

Table II. Sediment yield (u) parameter values (ton/km/yr) from GVRD (1999) to estimate the annual fine sediment yield (AFSY) from forest roads in their three managed watersheds (Seymour, Capilano, and Coquitlam). The loss ratio was determined by GVRD (1999) after the results from Reid (1981) using the Universal Soil Loss Equation (Wischmeier and Smith, 1965)

	Use			
Road slope	Light	Moderate	Heavy	Loss ratio
0 to 2.5%	0.2	2.1	25	0.7
2.5 to 7.5%	1.9	21	250	0.8
7.5 to 12.5%	5.1	57	675	0.9
>12.5%	10.5	105	1250	1.0

Separating road and non-road surface-related sedimentation

The second component of the methodology estimates the total sediment yield (sediment from all sources in the watershed) by incorporating daily hydrologic and SSC data. Hence, it is necessary to obtain the daily average values of suspended sediment concentrations (SSC_d) (mg l^{-1}) and discharge (Q_d) (l day^{-1}) from which the suspended sediment yield for day d (L_d) is determined:

$$L_d = SSC_d Q_d 10^{-9} \tag{2}$$

The total sediment yield generated by all sediment sources for the entire time series (T) is the sum of individual values of L_d and is expressed in tonnes. The next step is to separate the daily suspended sediment loads from those generated by road surfaces:

$$r_d = \frac{L_d \sum_{y=1}^{y} AFSY}{T} \tag{3}$$

$$n_d = L_d - r_d \tag{4}$$

where r_d is the SSC generated by the entire road surface network on day d; n_d is the non-road surface-related suspended sediment load on day d; T is the total sediment yield, which incorporates all sediment sources; and y is the number of years in the data set. In this context, non-road surface sediment includes sediment generated by mass movements which may be related to the road network or other human activities. Essentially, L_d/T represents the proportion of the time series' total sediment that occurs on day d, and that fraction is then used to parse out the total AFSY exclusively due to road surfaces into daily quantities (Equation 3). The total sediment yield implicitly includes all sediment sources whether road or non-road related. Although road surface-generated sediment is initially high immediately after road construction and can remain high over long periods of time (Hagans *et al.*, 1986), it is eventually moderated over time by natural revegetation and soil stabilization (Beschta, 1978). We assume that the non-road surface-related and road surface-generated sediments

Table III. Delivery ratios estimated by GVRD (1999) from field measurements of sediments that would potentially reach the stream considering the slope of the terrain and the number of ephemeral or major steams in the watershed

Slope of the terrain	No major or ephemeral streams	One ephemeral stream but no major streams	Major stream or more than one ephemeral stream
0 to 27%	0.05	0.3	0.5
28% to 49%	0.3	0.5	0.8
>50%	0.5	0.8	1

represent constant proportions and ignore the initial high fine sediment pulse from road construction, concentrating instead on the long-term chronic sediment inputs caused by use. Naturally occurring fine sediment yield is the total fine sediment yield for that day minus the fine sediment yield accounted for by road surfaces (Equation 4).

Simulating the scenario-specific time series

So far, we have described a method to estimate daily road surface and non-road surface-related sediment yields (Equations 3 and 4) under the current (baseline) conditions. Before linking changes in the number and magnitude of road-related SSC events to changes in road density and use, we describe the equations that allow us to simulate these changes using the time series data estimated in Equation (3). The following equation transforms r_d values based on a single parameter:

$$f_d = e^{\rho ln(r_d)} \tag{5}$$

where f_d is the transformed simulated daily values (tonnes day^{-1}) for a day (*d*); ρ acts on r_d values, which causes changes in the number and magnitude of extreme events in the time series. We chose an exponential-logarithmic function because it simulated the peak sediment flux events more faithfully than the linear form. Values of ρ must be greater than zero. As ρ increases, the magnitude of large events is amplified; as ρ decreases, the magnitude of small events is amplified. Thus, changes in ρ can affect the number of events above or below specific thresholds. The ρ values are assumed to be inversely proportional to the density of roads, under the assumption that greater road density provides more low permeability surfaces intercepting precipitation and channelling surface and sub-surface water to stream channels, thereby, increasing the peak discharge and the number of extreme flow events, independent of the level of use of the roads (Wemple *et al.*, 1996). Calculation of ρ is explained in more detail in the case study.

Equation 5, however, does not conserve the total sediment yield produced by changes in road density, which is necessary because we assumed that even though extreme events may change in quantity and or magnitude, the sediment availability remains the same. Equation 5 needs to be adjusted to produce a time series whose total SSC is at the desired level:

$$g_d = \frac{\phi R f_d}{\sum\limits_{d=1} f_d} \tag{6}$$

where g_d is the simulated road surface-related daily values of suspended sediment (tonnes day^{-1}); f_d is defined as in Equation 5, ϕ changes the total volume of road surface-related SSC for the whole time series (a value of 1 maintains the original time series' total volume); and R is the total suspended sediment yield generated by roads for the entire time series under the baseline conditions and is estimated by summing the AFSY overall years (which is the same as summing r_d from Equation 3 over the entire time series). The ρ =1 and $\phi = 1$ condition represents the baseline scenario. Relating values of ρ and ϕ to changes in road density and use is explained later in the case study. By adding g_d (Equation 6) and n_d (Equation 4), we obtain the final simulated values (λ_d) (tonnes day^{-1}):

$$\lambda_d = g_d + n_d \tag{7}$$

which are back-transformed into concentration units (mg l^{-1}) using daily discharge. The sum of all λ_d values for the length of the time series represents the total sediment yield (λ_*) specific to combinations of ρ and ϕ which include changes in both the number of events over a specific threshold and the magnitude of these events. The threshold definition is explained in more detail below. The final output of the model is a time series composed of discrete average daily values of concentration λ_d expressed in mg l^{-1}. Parameter estimation is specific to the watershed of interest (See case study for details below).

MODEL APPLICATION: CASE STUDY

Watershed

To demonstrate how the model can be applied, we selected the Chilliwack River watershed due to its aquatic habitat value, geographic location, data availability, and because there is an extensive logging and road-building history. The Chilliwack River is a tributary of the Lower Fraser River, and it is located in the Skagit Range of the Cascade Mountains, British Columbia (Figure 1). The river is renamed the Vedder River when it flows onto the floodplain of the Fraser River. The watershed has a drainage area of approximately 1230 km^2 (Mweempwa, 1993) and ranges from 13 m to 2283 m above sea level in altitude (Barlow *et al.*, 2003). Most precipitation falls from October to April. Snow accumulations of up to 5 m occur at and above 1500 m elevation and yearly rainfall averages 2500 mm in the valley bottom (Brayshaw, 1997). The Chilliwack River basin consists of a number of sub-basins, some of which contain important fish habitat. The Chilliwack River is gravel bedded throughout the reach of interest. Silt and clay-sized sediment (<63 μm) are carried as washload, and there are no significant fine sediment storage elements in the channel (Scott *et al.*, 1993; EBA Engineering, 2001). A portion of the watershed lies upstream of the Chilliwack Lake, which is an effective sediment trap. Sediment generated from the sub-basins contained in this portion is not detectable below the lake outlet and therefore not

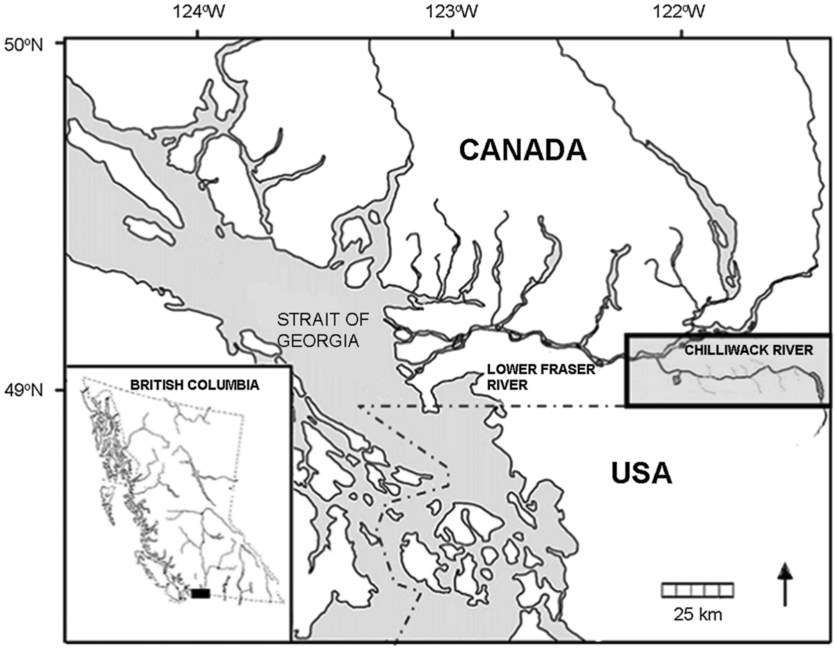

Figure 1. The Chilliwack River, a tributary for the Lower Fraser River

included in this analysis. The watershed has been subject to logging, road construction, and road use for at least a century. A large proportion of the roads are used for recreation and resource access. An assessment of the forest road conditions was completed in 1995 by SNC-Lavalin (contracted by the Ministry of Forest and Range, British Columbia). The contractors performed an inventory of forest roads in the watershed and evaluated the sediment-related risk for fish habitat. Intensive forestry activities in the watershed have resulted in the alteration of the flow regime and the generation of forestry-related landslides that remain a concern, particularly for their potential to increase fine sediment input into the main channel (DFO, 1995; Boyle *et al.*, 1997).

In our model application, we used several parameters (Tables II and III), employing information that was readily available from neighbouring watersheds used in the Metro Vancouver model including the Seymour, Capilano, and Coquitlam watersheds. The Chilliwack River shares many geographic, geomorphic, and hydrological characteristics with the watersheds employed (Table IV), but presents some terrain differences. For this reason, we adjusted some of the physiographic parameters such as delivery ratio, terrain slope, and road slope found in Reid (1981) and used in Equation 1 to estimate the AFSY (Table V).

Hydrologic and sediment data

The Water Survey of Canada (WSC) measured daily averaged SSC (mgl^{-1}) from 1965 to 1976, and discharge (ls^{-1}) from 1965 to 2006 at the Vedder Crossing station (station number 08MH001). SSC data provided by the WSC is a mix of direct sampling and estimates from SSC–discharge curves. We assumed that the SSC dynamics in the river in the period represented by the data are still valid for the present and future if road density and use remain similar, although changes in the sediment sources over time might lead to shifts in the SSC–discharge relation. We extrapolated the existing time series to generate baseline SSC values from 1977 to 2006 using a linear mixed-effects model that accounts for seasonality and hysteresis effects caused by changes in the sediment sources (Araujo *et al.*, 2012). Data from 1965 to 2006 (42 years) were used to parameterize Equation 2.

Forest road data

Road data for the watershed were extracted from EBA Engineering (2001). EBA estimated there was 541.2 km of permanent forest roads in the entire watershed by 2001, after removing from service the 153 km of roads that were designated as high priority for deactivation (inventoried by SNC-Lavalin in 1995). GIS data were also available from the Chilliwack Forest District, but we decided to use data from EBA (2001) instead because some licensee and spur roads (temporary roads) mapped in the GIS data remained active due to funding and other constraints on deactivation (Allan Johnsrude, BC Ministry of Forest and Range, pers. Comm., April 12 2010).

Table IV. Comparison of the characteristics of the Capilano and Chilliwack River (CRW) Watersheds

Watershed characteristic	Capilano Watershed	CRW
Climate	- Maritime	- Maritime and continental (4)
Average annual precipitation (mm)	- Lower elevation = 3159 mm - Higher elevation = 4 500 mm (1)	- Annual rainfall averages 2500 mm in the valley bottom (5).
Geology	- Bedrock consists primarily of intrusive igneous rocks (1) - Gentle and moderate slopes, especially at mid to low elevations, are mantled by glacial till (2)	- Bedrock consists primarily of metamorphic, sedimentary volcanic, and sedimentary (sandstone) rock (4) - Valley bottom consists primarily of glacial, fluvial, and glacio-fluvial deposits (4)
Elevation (m)	- Pacific Ranges of the Coast Mountains (2) - 155 m to 1725 m (1)	- Skagit Range of the Cascade Mountains (5) - 660 m to 1200 m (6)
Biogeoclimatic Ecosystem Classification	- Coastal Western Hemlock Zone (CWH) and the Mountain Hemlock Zone (MH), with a very small area of the Alpine Tundra Zone (AT) (3)	- Coastal Western Hemlock zone and the Mountain Hemlock zone.(4)

(1) Greater Vancouver Regional District, 1999
(2) Brardinoni *et al.*, 2003
(3) B.A. Blackwell and Associates Ltd., 1999
(4) Fraser Valley Regional District, 2005
(5) Brayshaw, 1997
(6) EBA Engineering Consultants Ltd., 2001

Table V. Baseline scenario for the Chilliwack River watershed (CRW)

Slope of the roads	Slope of the terrain	Streams	Road use	AFSY (tonnes.year^{-1})
7.5 to 12.5°	28% to 49%	One major stream or more than one ephemeral stream	Moderate (one to four logging truck passes per day)	28 500

Forest road use scenarios

To model changes in road density and use, we employed simulated data based on the road-building strategy associated with mixed timber harvesting and the preservation of habitat of the Northern Spotted Owl in the Chilliwack Forest District of British Columbia (SOMP-curr defined in Table VI, Sutherland *et al.*, 2007). The simulated data was forecasted for a 100-year period using the Spatially Explicit Landscape Event Simulator (SELES) (Fall and Fall, 2001). The SELES output is given in kilometres of roads built per decade during 100 years, and it is specific for each land unit of the Chilliwack Forest District, including the Chilliwack River watershed (Figure 2). A proportion of the simulated roads would eventually have to be deactivated; for this reason, we needed to calculate the number of roads at equilibrium resulting from constant rates of construction and deactivation, details in next section. We assumed that all simulated roads added to the production of sediments in the watershed, independent of their location. The current road-building strategy was associated with three hypothetical use levels: Light, Moderate, and Heavy, as defined previously, yielding three scenarios and assuming uniform spatial road usage. One additional scenario represents the current number of roads in the watershed (as of 2006) and assuming moderate use (baseline), and a final scenario represents natural sediment generation only, where roads are absent. The latter is represented by the time series of daily values n_d. Thus, for our analysis, there were five scenarios, (k = 1:5), where k denotes the scenario.

Calculation of peak SSC (ρ) and volume (ϕ)

In Equation 5, parameter ρ represents changes in the number and magnitude of events over the threshold. of $\mathrm{SSC} > 25\,\mathrm{mg\,l^{-1}}$. We used this value because it is the permissive increase in suspended solids over background levels for industry projects affecting aquatic species habitat in British Columbia (Ministry of Environment of British Columbia, 2009). In this context, an extreme event is characterized by the average SSC in a day over this threshold. The volume parameter (ϕ) affects the total volume of suspended sediments transported by the river (Equation 6), and it is a multiplier derived from the proportional difference between the total suspended sediment yield generated by roads $R_{k=1}$ (baseline scenario, $k = 1$) and R_k of any other scenario (k). Parameter ϕ is not

Table VI. Forest road construction and use for selected scenarios in the Chilliwack Forest District. Sutherland *et al*. (2007) described different forest management scenarios based on the 1997 Spotted Owl Management Plan guidelines. The scenario SOMP-curr closely relates to current management practices within the Chilliwack Forest District in relation to the protection of Spotted Owl habitat (current plan)

Forest management scenario	Description	Use level	Annual fine sediment yield (tonnes year^{-1})	Length at constant age distribution (km)
Baseline	The current (as of 2006) total length of the road network in the Chilliwack river watershed (permanent roads).	Moderate	7274	541.2
No-Roads (Natural)	Assumes that all roads in the watershed have been removed. However, other sources of sediments still contribute to the potential changes in SSC.	NA	NA	NA
Current Plan (SOMP-curr)	Based on the current timber harvesting and road construction plan for the Chilliwack Forest District for 100 years. Implying that a minimum of 67% of Old Growth stands are reserved within long-term activity centres.	Light Moderate Heavy	806 8906 106 025	662.7

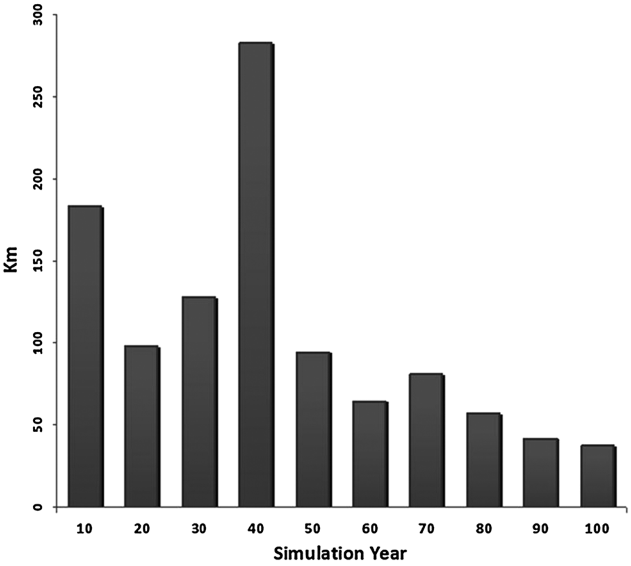

Figure 2. Length (km) of temporary forest roads forecasted for a 100-year period in the Chilliwack watershed under the current forest management plan (Sutherland *et al*., 2007) derived from the Spatially Explicit Landscape Event Simulator (SELES) (Fall and Fall, 2001)

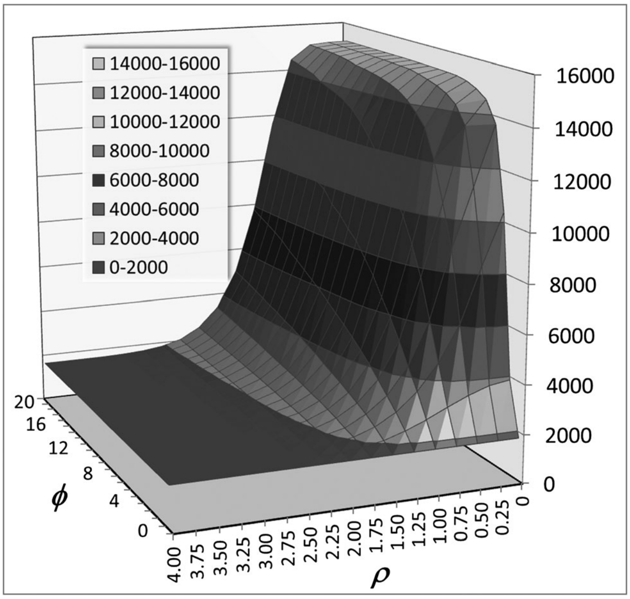

Figure 3. Number of observations exceeding the threshold of 25 mg l^{-1} for various combinations of ρ and Φ relative to the baseline ($\rho = 1$ and $\phi = 1$). The number of events >25 mg l^{-1} is sensitive to ρ values between 0 and 2 for any combination of ϕ values, increasing at higher values of ϕ

allowed to vary independently, except for experimental purposes.

Lack of data and the pervasive uncertainty in sediment dynamics make estimating ρ challenging. To overcome this limitation, we conducted a sensitivity analysis on the number of events exceeding the threshold of 25 mg l^{-1} for various combinations of ρ and ϕ in the model (Figure 3). The number of events >25 mg l^{-1} is sensitive to ρ values between 0.0001 and 2 for any combination of ϕ values. We assumed that $\rho = 2$ corresponds to a 100% decrease in road density, $\rho = 0.0001$ corresponds to a 100% increase in road density, and intermediate changes in road density were interpolated linearly. The reason for this assumption is that when $\rho < 1$, we observe an amplification of smaller events, which translates in a higher number of extreme sediment events over the threshold (25 mg l^{-1}) for the whole time series. The opposite occurs for values of $\rho > 1$. In our application, we use a value of $\rho = 0.8$ which is calculated from the percentage change in roads between the scenarios and the baseline road density. In Table VII, the baseline road length is 541.2 km and $\rho = 1$. In the scenarios, the length of the road network is 662.7 km which is an increase of 22.4%). The value of ρ is linearly interpolated so that the change in road length is inversely proportional change in ρ (e.g. 1.00 - 0.22 = 0.78, rounded to 0.8). Note that this approach is a simplification of the other factors that affect peak flows in large complex watersheds such as the connectivity of roads (Croke and Mockler, 2001; Takken *et al.*, 2008). However, the simplification is accounted for by the DR, which addresses the contribution of sediment from the road to the stream depending on the terrain characteristics (GVRD, 1999).

The volume parameter (ϕ), which affects the total volume of suspended sediments transported by the river (Equation 6), is a multiplier derived from the proportional difference between the total suspended sediment yield generated by roads $R_{k=1}$ (baseline scenario, k = 1) and R_k of any other scenario (k). The SELES model output specified the amount of new roads built in each decade for all scenarios depending on factors such as the availability of harvestable timber and the terrain slope on each scenario. However, the model output did not discriminate among the different road classifications (primary, secondary, and tertiary access, licensee, and spur roads), and the simulated roads would eventually have to be deactivated. For this reason, modelling individual annual road dynamics was not feasible. Instead, we calculated the number of roads at equilibrium, which results from constant rates of construction and deactivation. Thus, a constantly exploited watershed will theoretically reach its constant road age distribution at some point during the 100-year simulation period regardless of the availability of timber.

Following this rationale, we employed a formulation from finance theory in the form of Equivalent Annual Cost (EAC), or the cost of utilizing a long-lived asset (Bierman and Smidt, 1984). EAC works under the assumptions that (1) road-building cost is directly proportional to the length of the road network in the watershed, (2) timber is the asset, and (3) the road construction cost is one of the costs that society incurs to access the timber. Thus, the number of roads at equilibrium was estimated using the discount rate and the depreciation rate for a utility, based on the forest road construction data extracted from SELES. The discount rate employed was 4%, a typical rate used in forest resource economics.

For a scenario (k), the total length of the road network (i) at equilibrium ($\Psi_{i,k}$) is then the sum of the number of permanent roads in 2006 (541.2 km) plus the roads at equilibrium. In each scenario, $\Psi_{i,k}$ replaces the length of the road network (l_i) when estimating $AFSY_{i,k}$ in Equation 1 such that

$$AFSY_{i,k} = \psi_{i,k} u_i (LR_i)(DR_i) \tag{8}$$

In addition, the volume parameter for each scenario (k) is calculated as:

$$\phi_k = \frac{R_{i,k}}{R_{i,k=1}} \tag{9}$$

where $R_{i,k}$ is the sum of $AFSY_{i,k}$ across all years in the scenario-specific data set. Parameters values for ρ and ϕ are shown in Table VII.

Sediment yield with respect to use and density

The results from the simulations suggest that the road use level does affect sediment yield (Figure 4). For example, an increase from 15% to 30% in road density causes an increase in the daily average SSC of ~12 mg l^{-1} for moderate use, but the same increase in density for heavy use increases the daily average SSC to ~55 mg l^{-1}. These results agree with previous road surface sediment generation studies (Beschta, 1978; Reid and Dunne, 1984; Wemple *et al.*, 1996) in that heavier road use generates considerably more sediment than lighter road use. As road use levels increase, the number of observations exceeding 25 mg l^{-1} increases too, and the effect of road density becomes more evident (Figure 5). For our scenarios, there was little difference in the

Table VII. Estimated parameter values of ϕ and ρ, Annual Fine Sediment Yield (AFSY), and changes in density with respect to the baseline for all forest management scenarios

Road use	Forest management plan	Length of road network (km)	AFSY tonnes. year^{-1}	ϕ	Density of roads km.km^{-2}	% increase in density with respect to baseline	ρ
Moderate	Baseline	541.2	7274	1.00	0.41	0.00	1.00
None	No roads	0.0	0	NA	0.00	−100.00	NA
Light	Current plan	662.7	806	0.1	0.50	22.4	0.8
Moderate	Current plan	662.7	8906	1.2	0.50	22.4	0.8
Heavy	Current plan	662.7	106 025	14.6	0.50	22.4	0.8

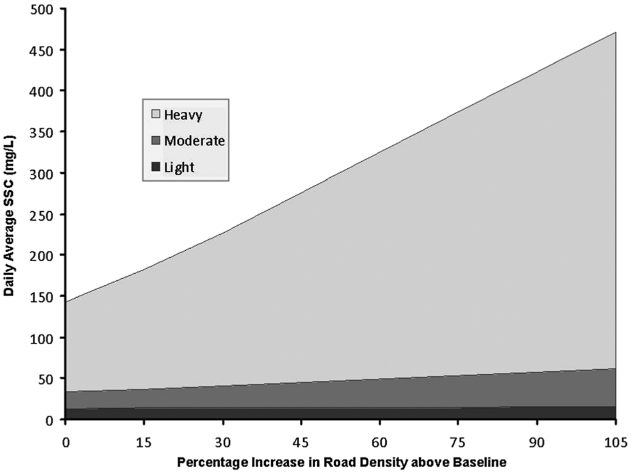

Figure 4. Daily averages of SSC under different conditions of road use for increasing road density over the baseline (simulated period)

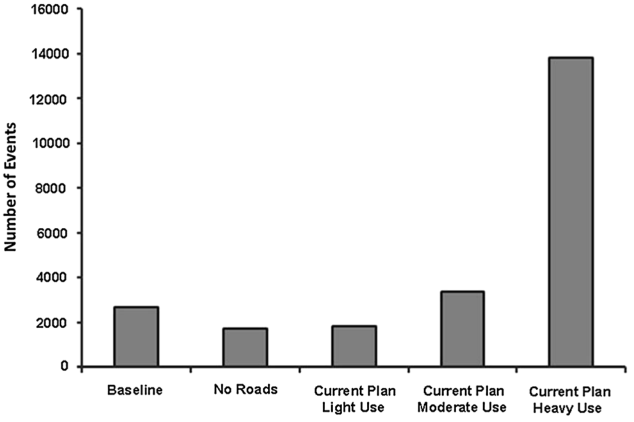

Figure 5. Number of observations exceeding 25mg l^{-1} per scenario during the simulated period

production of sediment except when road use becomes heavy (Figures 6). For the current management plan, in which road density is the same across scenarios, there is almost an eightfold difference in the number of extreme events between light and heavy road use levels (Figure 5).

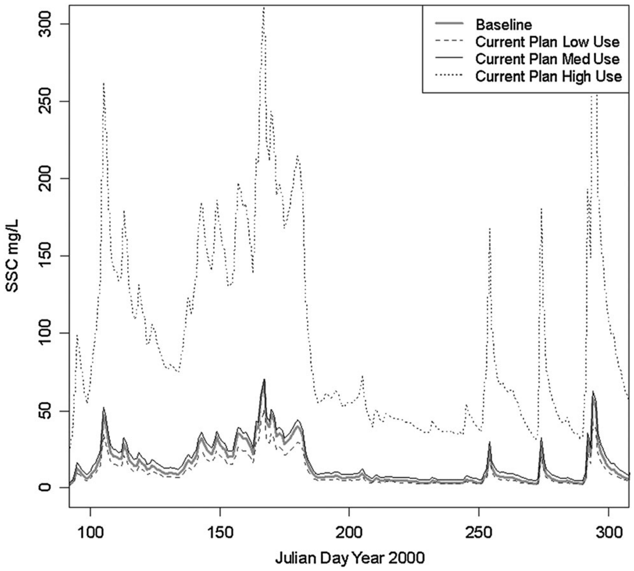

Figure 6. Simulated changes in SSC for (Julian days 100 to 300, year 2000)

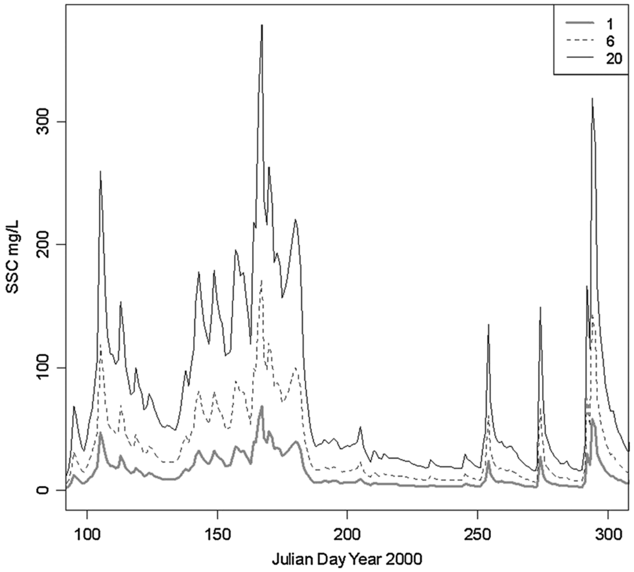

Figure 7. SSC time series modified by Φ parameter values 6 and 20 with respect to the baseline (keeping ρ =1 to observe the impact of varying Φ values) for the Julian days 100 to 300 in year 2000

Parameter influence on the magnitude and number of events

Parameter ϕ affects both the magnitude and the number of extreme sedimentation events in the watershed by modifying the volume of sediment that enters the stream (Figure 7). Deactivated roads produce very little sediment because these are not subject to traffic (Reid, 1981). Parameter ρ, which influences how the peak SSC in the time series will change for any given road density conditions, amplifies smaller or larger events depending on its value with respect to 1 (Figure 8). Smaller ρ values tend to increase the number of extreme sediment events that are greater than 25 mg l^{-1}. The model suggests that a watershed with a high density of roads will tend to cause a higher number of sediment events exceeding a threshold than a watershed with a lower density of roads. When comparing the influence of the two parameters, the simulation results suggest that ρ has a smaller effect than ϕ for the simulated road building conditions in the study watershed where road density increases by ~22% with respect to the baseline scenario (Table VII).

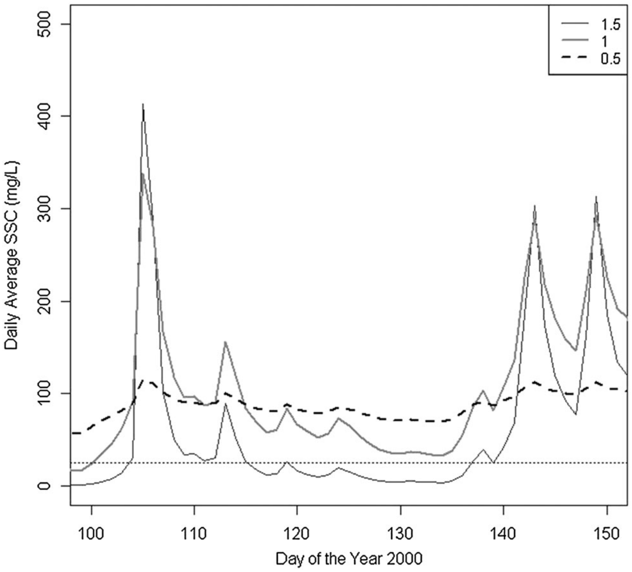

Figure 8. Sample of simulated time series of daily average SSC (mg/l) for the days of the year 100 to 150, year 2000, modified by ρ parameter values 1.5, 1, and 0.5 with respect to the baseline while keeping $\Phi = 1$ (as in the baseline scenario) to observe the impact of varying ρ values. The threshold of 25 (mg/l) is marked by the dotted line

DISCUSSION

The combination of site-specific data and theoretical considerations employed in this study allow for estimation of sediment yield from forest road surfaces where there is a time series of hydrological data, but it is not feasible to perform field work. Our goal was to provide a framework within which road surface sediment delivery can be investigated in data-limited situations. Our modelling approach has advantages over other techniques in that it contains few parameters, which make it more amenable for generic use in many watersheds. It requires only a time series of SSC and discharge data as well as a general inventory of roads and terrain characteristics. Operations such as validation, uncertainty analysis, and extension of complex models to ungauged watersheds using regional calibration methods can be very challenging compared to a less complex model such as the one introduced here (Limbrunner *et al.*, 2005). In addition, employing a time series approach makes it easier to develop extrapolation models for watersheds of similar characteristics (Powers and Van Cleve, 1991). Another advantage of this approach over conventional field-based methods is that it provides the opportunity to study the hydrologic and sediment response of road use on time scales that go far beyond the field observations. For example, this simulation technique could allow researchers to explore potential changes in the hydrology of watersheds as a result of future climate change. Some authors suggest that climate change in British Columbia will increase the number and magnitude of rainfall events that will, in turn, have a direct influence on the number of peak discharge events (e.g. Groisman and Easterling, 1994; Rodenhuis *et al.*, 2007). It is not clear how these changes will impact basin sediment yield, and a simulation model such as this may help bound what could be considered reasonable expectations for these impacts.

Some care needs to be taken with interpreting our results because the model does not account for sediment delivery to channels that are the result of road-related mass movements, which generate a significant amount of sediments in many steep watersheds. Care also should be exercised because the model is not verified with field data. We could not field test the model because it would require observations at the watershed scale over the time scales at which the model operates (years, decades). As such, our results are hypothetical and should not be misinterpreted as evidence that forest roads dominate sediment yield in watersheds, relative to landslides or other mechanisms. Nevertheless, the framework we present provides an opportunity for hydrologists and managers to forecast some of the potential consequences of forest road construction and use on the sediment flux of a watershed, which can be helpful in designing strategies to mitigate negative sediment-related effects on hydrological and biological processes. Long-term detrimental impacts on ecological processes are likely to result from chronic sediment sources, like road surfaces.

In our case study, lower sediment yields were more effectively accomplished by limiting the use of available roads than by controlling the road density alone. However, the model omits the impact of roads on mass movements in a watershed, and the effect of road density is probably more substantial than the model predicts. There is evidence that even if roads are deactivated and treated by restoring the natural hydrology by decompacting the road surface and removing unstable segments, they continue to produce sediment. Treatment of abandoned logging roads in California only reduced sediment production by ~25% compared to untreated roads (Madej, 2001). As such, lacking to incorporate mass movements into the model represents a limitation that needs to be addressed in further model development. Nevertheless, our model provides a method to estimate fine sediment production from road surfaces under a variety of forestry activity scenarios.

Our modelling approach has some other limitations. For example, it does not consider other management factors such as road construction techniques and sediment control measures that can decrease the road surface-related sediment input to streams (Reiter *et al.*, 2009). For this reason, the model provides trends in road surface-related sediment yield due to changes in forest road density and use rather than an accurate estimate of the total watershed sediment yield. A major assumption of our approach is that the number of forest roads will eventually reach equilibrium so we did not have to model individual roads when estimating the long-term chronic sediment production. Thus, the model may not accurately represent the temporal patterns of forest road dynamics. The model also does not include other human sediment-generating changes in the watershed or land use activities.

A limitation common to ours and other modelling approaches are the errors associated with estimating the AFSY using the SSC and discharge field data. Errors arise because suspended sediment samplers (point-integrated, depth-integrated, or simple bottle grab samples) only collect instantaneous samples of SSC that can vary substantially through time due to turbulence in the water column. Topping *et al.* (2007) examined the error associated with depth-integrated suspended sediment sampling and found errors of 8% in suspended silt–clay concentration, 22% in suspended sand concentration, and 12% in the median grain size. Others have reported errors of similar magnitude (e.g. Smith *et al.*, 2003a,2003b: 5–10%). Biases also arise due to the sampling frequency and timing. Most samples are collected during high flows, and replicate samples are rarely obtained. When using up to 12 samples, error ranges between 14 and 73% are reported (Webb *et al.*, 1997; Phillips *et al.*, 1999; Smith *et al.*, 2003a,b). Biases may also arise from the rating curves. Using a power function based on a nonlinear least squares method and logarithmic data transformation, Asselman (2000) calculated that sediment loads were underestimated by 1% and 12%, respectively. However, Mweempwa (1993) analyzed the sampling techniques employed by the WSC concluding that the SSC used here are accurate to ±10% for the Chilliwack River suggesting a limited effect on the model results.

CONCLUSION

We developed a simulation model that uses a time series of hydrological and suspended sediment data and the watershed's road and terrain characteristics to explore the effects of different road management scenarios on road surface-induced suspended sediment into streams. The model allows for changes (magnitude and peaks) in a simulated time series, taking as a reference, a predetermined threshold. In addition, the method allows isolating non-road surface-related SSC from that produced by forest road surfaces. The model was applied to a case study of road use scenarios for the current management strategy of habitat of the Northern Spotted Owl in the Chilliwack Forest District in British Columbia. Information derived from the model could assist resource managers with planning effective conservation of natural aquatic resources in watersheds that face changes in their road networks in the absence of extensive field data. This method is an attempt to overcome field data limitations by using an empirical relation between SSC and traffic variables and could be potentially used with other tools to develop a comprehensive watershed management approach.

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