ASSESSMENT OF EFFECTS OF FOREST HARVESTING ON STREAM SEDIMENTATION: A FOCUS ON COASTAL AND CENTRAL INTERIOR FOREST WATERSHEDS OF BRITISH COLUMBIA

by

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Abstract

Stream sedimentation issues resulting from forestry practices are prevalent in the province of British Columbia (BC). The impacts of riparian forest harvesting on the sediment regime of streams are of concern because of extensive commercial use of forest resources in BC. Forestry practices can alter the natural sediment balance and lead to abnormally high rates of sediment input resulting in increased concentrations of sediment in the water body and increased deposition of sediment on the stream bottom. The increase of sediment yield driven by forestry operations can reduce the storage capacity of reservoirs and degrade the water quality for human drinking, industrial, and recreational uses. Sediment inputs that exceed the background level and turbidity can also increase the risk to the survival and the integrity of aquatic ecosystems. Riparian forested areas in both coastal and interior plateau forest watersheds need careful considerations of riparian buffers and best management practices to avoid excessive sediment delivery into stream networks. Also, quantitative studies need to be conducted to compare different harvesting methods and provide forest management planner better suggestions to achieve both economic and environmental objectives. In general, a holistic approach is required to control sediment production across different landscapes. What's more, a better understanding of the interaction between sediment dynamics and forest harvesting and continuous implementation of best management practices will result in fewer problems.

Key words: forest harvesting, riparian forest, stream, sediment, Coastal and Central Interior watersheds, British Columbia

Table of Contents

List of Acronyms and Abbreviations

BC: British Columbia

BEC: Biogeoclimatic Ecosystem Classification

BMPs: Best Management Practices

CWH: Coastal Western Hemlock

MFLNRO: Ministry of Forests, Lands & Natural Resource Operations

MOE: Ministry of Environment

RMA: Riparian Management Area

NCI: North Central Interior

SCI: South Central Interior

UBC: University of British Columbia

List of Figures

List of Tables

1. Introduction

1.1 Riparian forest harvesting issues

The forest can protect soil and reduce erosion rates and sediment delivery to surrounding watersheds (Elliot, Page-Dumroese, & Robichaud, 1998), but the increase of sediment inputs driven by forestry operations can affect water quality, fish habitat, and channel stability. In the Province of British Columbia (BC), the impacts of riparian forest harvesting on the sediment regime of streams are of concern because of extensive commercial use of forest resources (Jordan, 2006). Riparian logging has widespread influences on the streams, from altering watershed physical hydrology, shifting geomorphic structure, increasing sediment inputs (Moore & Wondzell 2005), affecting fish populations (Larkin et al., 1998; Mellina & Hinch, 2009) and benthic communities (Melody & Richardson, 2007). Forest operations remove ground vegetation and disturb forest soils resulting in an increased risk of soil erosion. Therefore, soil erosion caused by riparian forest harvesting will potentially add unusually large amounts of sediment to the water body, thereby significantly affecting stream physical, chemical and biological process (Birtwell, 1999). Natural sediment inputs were controlled by local climate, soil conditions, native vegetation types, and watershed characteristics. A stream can be considered to be unnaturally or excessively impacted by sediment when human activities are contributing sediments (Environment Canada, 2016). Harvesting activities can alter the natural sediment balances and lead to abnormally high rates of sediment input with the increases in the 20% to 40% range (Skaugset et al., 2013; Zegre, 2008). Forestry activities such as road construction and timber harvesting may increase sediment yield, but the implementation of best forest management and riparian area protection practices can effectively stabilize stream banks and intercept sediments. For instance, rehabilitation of stream bank and hillslope is feasible to reduce adverse impacts caused by riparian logging practice (Chatwin & Smith, 1992). Otherwise, since the 1960s a riparian buffer strategy has been effectively used as a practical mitigation measure to reduce the harvesting impacts on stream and fish habitat (Richardson, Naiman, & Bisson, 2012). The main functions of a riparian buffer include maintaining bank stability, providing shade and a source of large woody debris (Tschaplinski & Pike, 2010). Overall, the impacts of riparian forest harvesting on stream sedimentation are complex and may vary depending on the geographical locations, climate features, hydrological regime, watershed characteristics and logging methods.

The purpose of this essay is to understand how the timber harvesting activities influence the sediment dynamics (supply, transportation and storage) in a forested area. The study areas of this literature review will be focused on watersheds located in the coastal and interior plateau regions of BC because the majority of watershed studies related to logging and sediment interaction were conducted in these two areas. There are some differences in hydrological regimes, stream networks, forest types and harvesting systems between coastal and central interior forested watersheds. Thereby, it is likely to see how forest harvesting activities differently affect sediment dynamics between these two areas. Also, previous studies evaluating the impacts of forestry and sedimentation interaction in the coastal and central interior forest watersheds will be discussed as well.

1.2 Stream sedimentation and its influences

1.2.1 Water quality

The primary anthropogenic sources of sediment to forest watersheds are logging practices adjacent to riparian features, surface erosion from logging roads and mass wasting after forest operations. Extensive tree cutting in the riparian area may not only increase natural water runoff but also accelerate soil disturbance and affect water quality (Moore & Wondzell 2005). Soil erosion can increase fine sediment delivery to stream channels while changes in hydrologic regimes can increase stream flow and then result in sediment transport increase (Gomi, Moore & Hassan, 2005). Excessive sedimentation after logging activities can come in the form of both suspended and bedload sediments (Turner, 2007). Increases in sediment flux can be demonstrated as both high suspended sediment concentrations in the waterbody and increased sedimentation of streambed substrates. Suspended sediment is an important pollutant in stream channels causing water quality deterioration resulting in aesthetic issues, higher water treatment expenditures, fisheries resource declines, and severe ecological degradation of aquatic environments (Bilotta & Brazier, 2008). As noted by Campbell & Doeg (1989), high concentrations of suspended sediment exist in a water body primarily during the relatively short period of high stream flow. Nevertheless, deposited sediment on the streambed is far more significant than suspended sediment which can result in long-term harmful impacts to fish and invertebrate populations (Campbell & Doeg, 1989). Other adverse impacts include reducing the storage capacity of reservoirs, destroying wetland areas, and degrading the water quality for human drinking, industrial, and recreational uses (Turner, 2007).

1.2.2 Aquatic Ecosystem

Elevated levels of sediment input (i.e. sediment influx exceeds the background level) and turbidity caused by logging activities and road construction can increase the risk of the survival of aquatic organisms (Birtwell, 1999). Stream sedimentation issues resulting from poor forestry practices are prevalent in BC and affects both spawning and rearing habitat for salmonids, and their aquatic food chain (Larkin et al., 1998). Increased suspended sediments reduce water clarity and decrease the penetration of light into the water, then affecting fish and invertebrate species foraging activities. Increased concentration of inorganic sediment in the stream can also impair biological functions for benthic communities. Benthic invertebrates including numerous species of insects, molluscs and crustaceans are highly dependent on their surroundings. Suspended sediment can affect benthic invertebrates through abrasion and scouring process, then causing damage to exposed respiratory organs or making the organism more susceptible to predation (Bilotta & Brazier, 2008). Shaw & Richardson (2001) research also showed that total abundance of benthic invertebrates and family richness was reduced as the result of increasing sediment pulse duration.

2. Coastal and Central Interior BC

There are eight terrestrial regions of the Province of BC (Figure 1) based on their distinctive geographic features and historical development (McGillivray, 2011). In this essay, coastal and central interior (plateau) forest watersheds are the main study areas and this section provides the background information of geographic features, climate, hydrological regimes and forest covers. The Coast Forest Region (Figure 2) which completely manages coastal forests of province BC, covering a total of 16.5 million hectares, is bounded to the east by the Coast Mountain and Cascade Ranges, consists of North & Central Coast region, south Lower Mainland and west islands including Queen Charlotte Islands and Vancouver

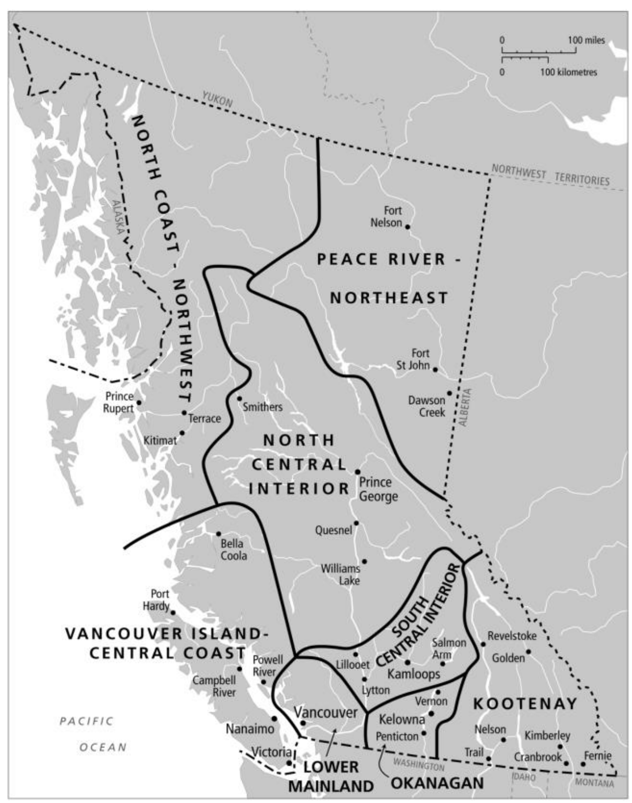

FIGURE 1. REGIONS OF BRITISH COLUMBIA. (SOURCE: MCGILLIVRAY, 2011)

Islands (Ministry of Forests, Lands & Natural Resource Operations, 2011). Coastal mountain areas support temperate rainforests under a maritime climate, and there are extensive snow and ice cover at higher elevations. The forests have been heavily exploited for their valuable timber resources in this region since the 1890s.

FIGURE 2. BRITISH COLUMBIA FOREST LAND MAP: WEST COAST FOREST REGION (BRIGHT GREEN SECTION). (SOURCE: MFLNRO, 2011A).

There are diverse topographical features in the coastal area including coastal lowlands and broad alluvial valley bottoms associated with major rivers, e.g. Fraser River is the largest river systems in BC and is important to the salmon fishing industry. The stream and lake networks within coastal forests have valuable fish populations, especially the Pacific Salmon (*Oncorhynchus* spp.). There are no large rivers (>120 m) on Vancouver Island, but many small rivers and streams which are significant for fish habitat are more susceptible to adverse impacts caused by riparian logging than larger rivers (Richardson et al., 2010). Coastal Forest Region is also well recognized as temperate rainforest (Slaymaker, 2000) which includes two primary biogeoclimatic zones (BEC): Coastal Western Hemlock (CWH) and Mountain Hemlock (MH). Hydrologic regimes in coastal watersheds can be broadly defined as either rain & rain-on-snow dominated (low elevation) or snowmelt-dominated (high elevation) (Moore & Wondzell, 2005). Flow regimes in small and low-elevation streams were driven by winter rainfall while those of higher elevation are driven by winter rain, rain-on-snow, and spring snowmelt events (Hartman, Scrivener & Miles, 1996).

FIGURE 3. NORTH CENTRAL INTERIOR REGION

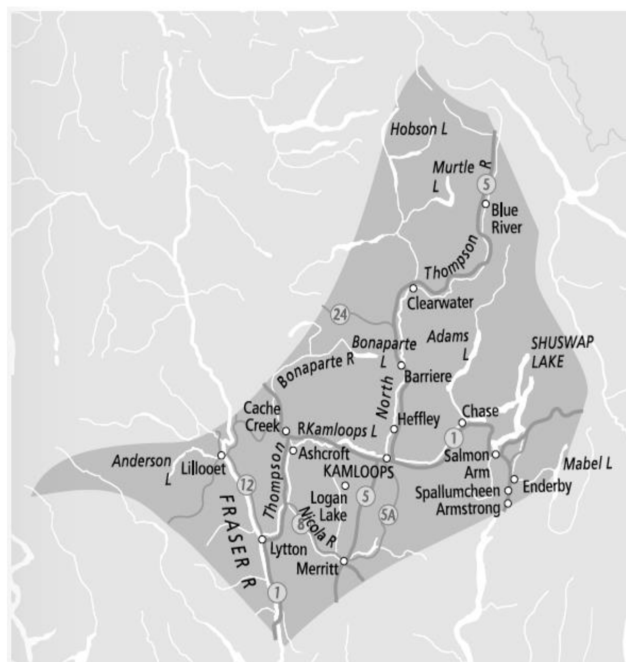

FIGURE 4. SOUTH CENTRAL INTERIOR REGION

The Central Interior of BC is mainly composed of North Central Interior (NCI) and South Central Interior (SCI) regions (Figure 1). As one of the largest regions in BC, NCI region is also defined as the Northern Interior Plateau. This area covers the northern half of the Fraser River watershed and includes Smithers and the Bulkley Valley on the west part (Figure 3). Mixed Pacific and Arctic air masses bring about increased precipitation, but this varies according to the different configurations of the mountain chains (Eaton & Moore, 2010). The SCI is largely identified by the Southern Interior Plateau which extends west of Lillooet to Revelstoke on the Columbia River, but the Thompson River system is the dominant watershed in this region (Figure 4). Forestry has been the most important industry since the middle 1960s when a pulp mill was established in Kamloops as well as sawmills and other forest product manufacturing plants sprang up throughout the region (McGillivray, 2011). Interior spruce forest region includes two primary BEC zones: Sub-Boreal Spruce (SBS) and Sub-Boreal Pine Spruce (SBSP). Thus, the cooler and drier Interior forest region are home to more trees of the pine and spruce variety. Snowmelt-dominated hydrologic regimes occur in the interior plateau where winter precipitation dominantly falls as snow and remains in storage until spring melt resulting in low stream flows through winter time and high flows in summer (Eaton & Moore, 2010).

3. Sediment cycle in forest watershed

A knowledge of sediment dynamics is helpful to understand the riparian logging and stream sedimentation interaction. The sediment cycle (Figure 5) starts with the process of weathering, i.e. particles or fragments are weathered or fractured from rocks which are the ultimate source of sediments (Environment Canada, 2016).

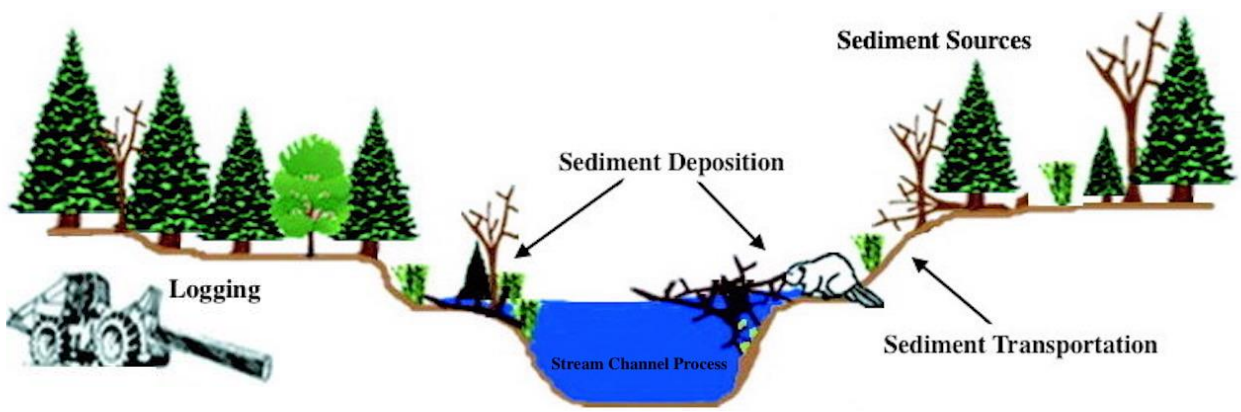

FIGURE 5. SEDIMENT SUPPLY, TRANSPORT AND DEPOSITION IN FORESTED WATERSHED WITH MODERATE SLOPE (SOURCE: MODIFIED FROM LUKE ET AL, 2007)

Sediment supply refers to the amount of sediment available for sediment transportation. Most of the materials delivered to a stream are so fine (silt and clay < 0.05 mm) that can be carried by any stream flow as suspended sediments (Hickin, 1995). In this context, sediment transport is limited by the size of sediment and transport of coarser material (coarser than fine sand > 125 μm) is largely capacity limited. Wind, glaciers, animal activities and human intervention all contribute to the erosion of the earth's surface (Schreier & Pang, 2015). The transportation process initiates from the land surface, then gullies, hillslopes (Figure 6), logging roads act as the functional pathways for sediment delivery. Water plays a major role in the transformation of the Canadian landscape by moving large amounts of soil, in the form of sediment (Environment Canada, 2016). The flows of water are the main carrier for in-channel sediment transportation, and forestry operations like logging and road construction have significant impacts on watershed hydrological characteristics. Annual water yield generally increased after logging practice in the coastal region, and in interior watersheds, harvesting has increased snowmelt-driven peak flows by up to almost 90% (Moore & Wondzell, 2005). Thus, the erosion process caused by increased stream flow may take place much faster. Suspended sediment transport and bedload movement are two primary sediment transport processes within stream channel (Figures 5&6). As mentioned before, stream flow supports the transportation of suspended sediments in the water body. However, the bedload transport which refers to the movement of particles or grains along the stream bed was supported by the bed itself (Hickin, 2004). Bedload sediments are largely consisting of sand (0.5 – 2 mm) and gravel (> 2 mm) with coarser fraction. Thus, bedload movement in many streams is uncommon or negligible at low flow but the transport can be active when stream discharge increases and exceeds critical shear stress (Hickin, 2004). Besides, changes in bedload movement and stream bank erosion caused by peak flow increases following logging practice can provide an additional source of suspended sediment (Jordan, 2006). In steep forested area (Figure 6), hillslope process which include surface erosion and debris flow plays a significant role in sediment transport down slopes and into channels. Once in the channel, input sediment either enters temporary storage locations or moves as suspended sediment, bedload and in debris torrents (Swanson& Fredriksen,1982).

Deposition or sediment storage is the final process in the cycle. Sediment carried by stream flow will ultimately settle to the bottom as water velocity decreases and loses transport energy (Ministry of Environment, 2016). Both suspended and bedload sediments can be deposited if stream discharge is low and then start moving again when discharge is sufficient to overcome a particle's Shield’s criterion. Excessive sediment deposition on streambeds can alter stream hydrological processes and degrade streambed quality (Kreutzweiser et al., 2009).

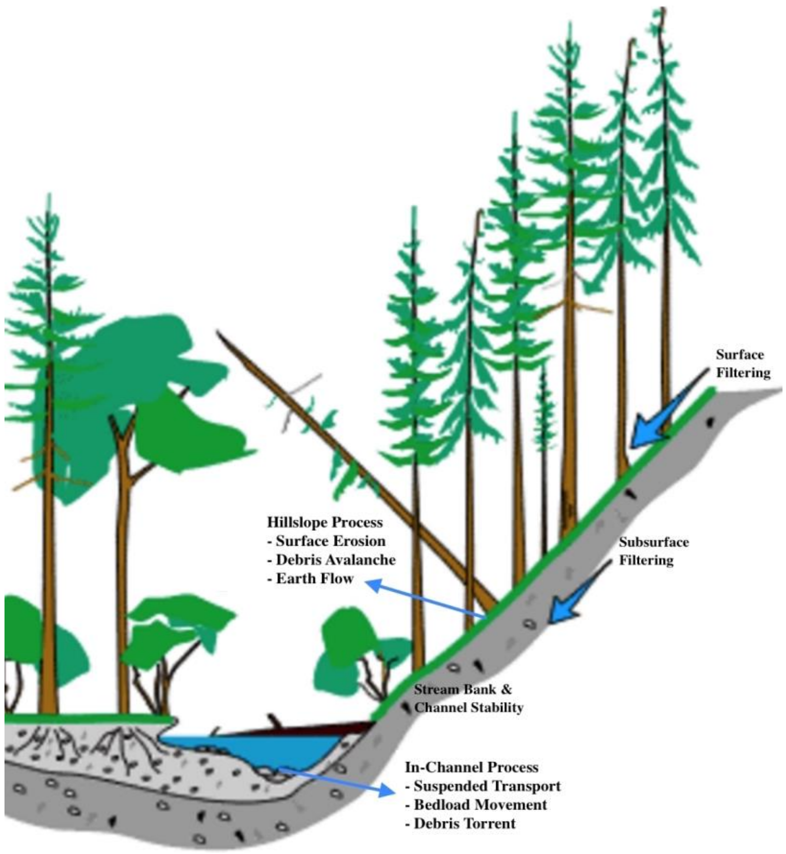

FIGURE 6. SEDIMENT TRANSFER PROCESSES IN STEEP FORESTED WATERSHED (SOURCES: MOE, 1999; MODIFIED FROM SWANSON& FREDRIKSEN,1982).

4. Primary sediment sources

4.1 Soil erosion caused by logging practice

Forest harvesting which directly causes loss of both overstory and understory vegetation cover creates a pre-condition for the increase in soil erosion rates. Logging practices such as landing, road constructions, and skidding trails may significantly increase soil compaction, reduce soil productivity and accelerates soil erosion. Besides, forest harvesting and road development can improve the delivery of water to soil and streams, resulting in acceleration of soil disturbance and initiation of debris torrents then making sediment becomes more available to the stream networks (Slaymaker, 2000). Study of frequency and yield of mass wasting on the Queen Charlotte Islands (Rood, 1984) showed that frequencies of debris slides increased by 30 times and debris flows increased by 41 times after harvesting, and results also indicated that 80% of the sediment production came from clearcut blocks while other 20% came from forest roads. Table 1 describes the main sediment sources that were collected from previous forest watershed studies in coastal and interior BC.

TABLE 1. SUMMARY OF PRIMARY SEDIMENT SOURCES AND THE CORRESPONDING IMPORTANCE

Sediment Source	Location	Forest management practice	Impacts on sediment dynamics	Importance	Citation
Logging activities	BC	Clearcut; Skiddering (Interior), Hoe-forwarder & Fell-buncher (Coastal)	Surface erosion increases sediment supply and increased runoff benefits delivery	Medium	*(Winkler et al., 2010)*
Road Construction	Coastal & Interior BC	Road fills, long unvegetated road fillslopes, unstable and large unvegetated cutslopes, crossing structures	Soil erosion & surface erosion bring more sediment supply; soil compaction increases erosion and transport	High	*(Tschaplinski, 2012)*
Landslides	Coastal & Interior BC	Clearcut; Unpaved logging roads	10-fold increase in sediment production	High	*(Slaymaker, 2000)*
Landslides & debris flow	Coastal BC	Clearcut; Hillslope logging, road building and stream crossing	Large amount of sediment supply	High	*(Jordan et al., 2010)*

The main negative impacts of logging activities on soil include soil compaction, rutting and puddling. Soil compaction refers to the process of increasing soil density by packing the particles closer together and reducing pore space, and resulting in reducing soil porosity decreasing water movement into and through the soil (McLellan, 2014). Rutting happens (especially under wet conditions) when the soil strength is too weak to support pressure from operating machinery (e.g. skidders). Rutting can affect the surface runoff and reduce water infiltration then increasing soil saturation and creating soil erosion (Grigal, 2000). Puddling process can alter soil properties as shearing forces can affect soil structure and porosity, then can lead to soil compaction and erosion (Grigal, 2000). Wet, fine-textured soils are more susceptible to puddling than coarse soils, so avoiding harvesting on wet conditions is the best approach to prevent puddling impacts (McLellan, 2014).

4.2 Hazards from roads

Erosion from forest roads was often considered as a significant source of sediment and a main contributor to stream sedimentation in forested watershed (Jordan, 2006). Reduced soil infiltration rates, increased slopes, removal of vegetation cover and interception of subsurface flow are several major factors that result in increased erosion potential of forest roads. All of these factors can also contribute to sediment transportation as a result of increasing the volume or the velocity of storm runoff (Grace, 2002). But, rainsplash, road surface textures and operational activities (e.g. road maintenance) are the main factors that contribute to forest road surface erosion (MacDonald & Coe, 2008). Some of sediment sources from roads might include delivery from road fills, long unvegetated road fills, unstable unvegetated cutslopes, soil erosion at crossing structures and road sections with steep slope nearby stream networks (Berry, 2004). Road crossings structures, particularly culverts can impede the water movement, sediments and fish activities in streams. For example, perched or blocked culverts can cause sediment or debris accumulations below them that blocked fish movements upstream (Tschaplinski, 2012).

In wet climate regions, roads can bring about 10 to 300-fold increase in the landslide erosion rates because of losing hillslope structural integrity (MacDonald & Coe, 2008). In particular, unpaved roads can increase sediment production rates by more than an order of magnitude as a result of road surface erosion. According to the results of assessment of the effects of roads on the post-harvesting condition of streams in both coastal and interior BC (Tschaplinski, 2012), forest roads were identified to be the most frequent cause of impacts to streams as two-thirds of total (1302 of total 1916 sample streams) impacted area were affected by inorganic sediments generated and delivered by roads. Besides, other main observed impact sources include logging machine disturbance in the Riparian Management Area (RMA), and falling & yarding activities both across and near stream. Nevertheless, not all eroded materials from road surfaces can reach the receiving water due to deposition process between the sediment initiation location, crossing structures (e.g. culvert) and streams (Fu, Newham, & Ramos-Scharron, 2010). Figure 6 shows surface flow is usually drained to ditches on the side of the road and then can be redirected by culverts. Sediment derived from road surface can reach the stream directly at crossings, and indirectly through diffuse, partial or fully gullied pathways (Figure 7), but transporting via crossing structures is the most efficient form of sediment delivery (Fu, Newham, & Ramos-Scharron, 2010) as sediment delivery to streams occurs primarily at road-stream crossings and secondarily by road-induced gully pathways (MacDonald & Coe, 2008).

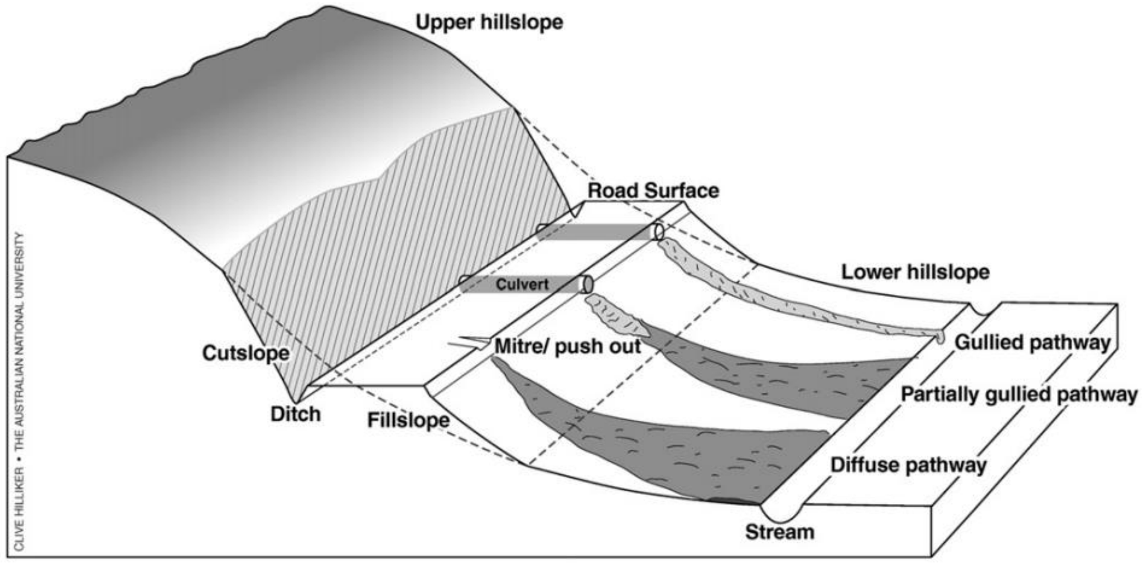

FIGURE 7. CROSS SECTION AND FEATURES OF A TYPICAL CUT-AND-FILL LOGGING ROAD (SOURCE: FU, NEWHAM, & RAMOS-SCHARRON, 2010).

4.3 Slope failure & Mass movement

Hillslopes are highly sensitive to impacts from removal of forest cover, hydrology, and soil conditions. Landslides and debris flow occur when gravitational forces and hydrologic conditions exceed the strength of the soil (Jordan et al., 2010). Sediment production and delivery in steep, forested catchments are typically dominated by low-frequency and high-magnitude erosion events such as landslides or debris flows (MacDonald & Coe, 2008). Hillslope failure, particularly in steep terrain, is a significant source of sediment to streams. Even in the absence of forestry, shallow debris slides and flows are especially common on the coastal region while large rotational rock movements are common in glacial sediments and volcanic bedrock in the interior BC (Geertsema et al., 2010). Debris slides are the simplest and prominent landslide type in BC and debris flow is a form of mass movement of saturated soil, rocks and vegetation. Nevertheless, forest harvesting practice indeed plays a significant role of accelerating hillslope failure process, especially in BC coastal forest watersheds (Jordan et al., 2010). Some studies of coastal watersheds (Brardinoni, Hassan & Slaymaker, 2003; Gomi, Moore & Hassan, 2005) showed that hillslope failure and mass wasting during or shortly after logging activities can contribute large amounts of sediment input and debris to stream networks because of still actively used logging road and unstable adjacent slopes. In south interior Redfish Creek region, five landslide events happened from logging roads during 1993-2003 and the estimated average sediment delivery to the creek is 25 tonnes per year (Jordan, 2006), but in most years, landslides contribute no sediment in this region which means the contribution of sediment from landslide events is a risk.

Landslide hazards are high in gully areas where steep slopes and drainage can interact with each other, resulting in debris slides. Debris slides initiated debris flows due to contribution of channel water are common in BC watersheds (Geertsema et al., 2010). However, Millard's (1999) study of debris flows in coastal BC showed that only 2% of debris flows were driven by high water discharges in the channel, which commonly happens in the interior regions of BC. Forest roads also may increase landslide events by disrupting the balance of driving and resisting forces acting upon and within hillslopes (MacDonald & Coe, 2008). The volume of sediment delivery is greatest from torrent and slash disturbed gullies by mass wasting and fluvial channel erosion, particularly in coastal watersheds (Slaymaker, 2000). The impacts of road development during timber harvesting is commonly recognized as the dominant reason for accelerated slope failure in the Pacific Northwest (Reid & Dunne, 1984). As concluded from Slaymaker (2000), it is difficult to avoid unstable terrain during road constructions due to poor knowledge of local terrain stability and it's easy to neglect the maintenance of road drainage structures as a result of a lack of good recognition of road crossing structures' requirements. Both of these non-integrated forest management practices are the main factors for road-related slope failures.

5. Results and Discussion

5.1 Interaction between Riparian Forest Harvesting and Stream Sedimentation

Slaymaker's research (2000) reviewed of the impacts of forest development in BC focused on the impacts on stream channels, slope stability, and sediment yield. The results showed that landslides and erosion have produced a 10-fold increase in sediment production from timber harvesting in BC mountain areas. Besides, debris flows and unpaved logging roads are the most significant contributors to sediment production (Slaymaker, 2000). In harvested areas, debris slides and flows produce sediments of 10^4 m^3/km^2/year whereas sediment production is 10^3 m^3/km^2/year in unharvested areas. Unpaved logging roads (covering <10% area of the watershed) generate about 10^3 m^3/km^2/year which is much higher that 10 m^3/km^2/year sediment production from surface erosion. Another example from Russell Creek watershed (Coastal BC), showed the most significant sediment sources are landslides on the sidewalls of incised stream reaches, which generally supply up to 60% of the sediment produced during storms while forest management was actively ongoing (Hudson & Anderson, 2006).

Logging activities can affect sediment supply by making it more available for delivery by causing more soil exposure, decreasing slope stability, destabilizing stream banks and depositing debris in stream channels and gullies (Church & Eaton 2001). Up-slope or streamside falling and yarding which are common logging practices in coastal forests can influence soil stability (more exposure and compaction), sediment supply and delivery to the stream. Also, soil disturbance may be only 2% in unharvested areas, but can increase to 16% in clearcut and yarded areas (Hartman, 2004). It is challenging to manage a high level of uses of forest resources in coastal region and mountainous terrain with shallow and unstable surficial materials makes the situation even more difficult (Hartman, Scrivener & Miles, 1996). Besides, coastal watershed drainages are also affected by high precipitation and severe storms, which cause much variations in hydrological regimes among watersheds with different sizes and elevations. Skidder is commonly used for timber harvesting in BC, particularly in Interior forest region, and can cause soil compactions and overland flow, and then leading to an increase of surface runoff and the magnitude of surface erosion (Winkler, 2010). Thereby, the accelerated soil erosion from skid trails may result in soil nutrient loss and increasing sediment output. However, different harvesting methods can cause different degrees of soil disturbance. Heli-logging, cable yarding system (e.g. skyline), or ground cable logging systems are commonly used on steeper slopes (>35% slope), and trees may be felled and removed with full suspension of logs by a helicopter without disturbing the site (Elliot, Page-Dumroese, & Robichaud, 1998). Also, a heli-logging study completed in Rennell Sound on the Queen Charlotte Islands (Krag, 1998) reported that conventional grapple-yarded slopes caused 8% mineral soil exposure while heli-logged areas only had 0.1–2.4% soil exposure and left lower levels of undisturbed forest floors.

Stream sedimentation has been recognized as a potential threat to the aquatic organism particularly fish and benthic communities. In recognition of this, many government-led environmental organizations have responded by establishing water quality guidelines and standards, which state recommended concentrations of sediment in the waterbody (Bilotta & Brazier, 2008). However, specific level of risk to stream ecosystem depending on the sediment levels generated and the sensitivity of the aquatic organisms needs to be considered (Birtwell, 1999). After a review of available documents and guidelines, DFO (2000) classified the levels of risk to fish and their habitat with corresponding sediment concentration, which was assessed using increased concentration above background levels (Table 1). These risk indexes are helpful to assess the detrimental effects of stream sedimentation caused by timber harvesting.

TABLE 2. THE LEVELS OF RISK AND CORRESPONDING SEDIMENT CONCENTRATION

Sediment increase ($mg \cdot L^{-1}$)	Risk to fish and their habitat
0	No risk
<25	Very low risk
25 - 100	Low risk
100 - 200	Moderate risk
200 - 400	High risk
>400	Unacceptable risk

Concentration of suspended sediment (sampled during snowmelt or rainfall events) after harvesting was studied through nine creeks in Central Interior watersheds of BC (Larkin et al., 1998). Results showed that mean suspended sediment at the 8 sites ranged from 25 – 72 $mg \cdot L^{-1}$ during two-month (May & June) study period except lowest value 21 $mg \cdot L^{-1}$ occurred at the lower section of Spruce Creek and highest value 233 $mg \cdot L^{-1}$ happened at Thursday Creek probably resulted from initiation of a mass wasting events (Larkin et al., 1998) associated with short period of time. But, the median suspended sediment which was suggested as a better measure ranged from 13 – 57 $mg \cdot L^{-1}$. Large-snowpack-caused spring runoff events were observed in all study streams and also was the main driver to peak value of sediment concentration. However, the pattern and degree of suspended sediment influx caused by high flows were varied among sampled sites which indicates that different hydrologic conditions and sediment sources can cause big variations among different study regions. Regarding adverse impacts on fish populations, lethal and sub-lethal effects on the resident and migratory fish populations were assessed during the study period (Larkin et al., 1998). Predicted severe effects included both short-term and long-term decline in feeding rates and success, moderate habitat degradation and physiological stress. As suggested in this study, hillslope and stream bank restoration are required in the central interior region to address and reduce suspended sediment input and adverse impacts on water and habitat quality (Larkin et al., 1998). A study of suspended sediment concentration and stream discharge during snowmelt in three headwater streams in the Central Interior also showed increased sediment input (peak concentrations were over 80 $mg \cdot L^{-1}$) after harvesting (Macdonald et al., 2003). However, the concentration of suspended sediment returned to levels at or below background conditions (i.e. pre-harvest prediction ranged from 25 – 30 $mg \cdot L^{-1}$) within three years in the highly preserved forest watershed. Besides, the infrequent and short duration of highest production of total suspended sediments (about 100 $mg \cdot L^{-1}$) was also indicated in this study. As concluded in this research, the riparian treatments were effective at protecting stream banks from physical damage, but windthrow disturbance in the high-retention watershed may eventually contribute to the sediment delivery to the channel.

5.2 Best Management Practices

Best Management Practices (BMPs) that applied to the riparian forest management can effectively prevent unacceptable changes to sediment input and other sources of pollution in streams (Broadmeadow & Nisbet, 2004). Some feasible and effective management practices that can reduce excessive stream sedimentation impacts include establishing a sufficient riparian buffer zone, enhancing bank stabilization, revegetating on erosion-prone soils and cut slopes in order to reduce sediment supply and intercept sediment transportation (Turner, 2007). Forest management plan widely adopts the riparian strategy to reduce sediment transport and control soil erosion, protect stream water quality, moderate shade and stream temperature, and maintain riparian ecosystem diversity and integrity (Broadmeadow & Nisbet, 2004). Best forest management practices are often implemented to allow timber harvest while achieving riparian management objectives. Riparian management strategies originally focused on protecting water quality and fish habitat, but now other environmental values like riparian wildlife were taken into consideration (Richardson, 2003).

Management practice in coastal watershed should focus on avoiding harvesting-related landslides and sediment production, and partial harvesting method is feasible to reduce landslide events compared with clearcutting practice on steep hillslopes (Jordan et al., 2010). Although some harvesting methods can theoretically reduce landslide frequency after logging, no quantitative research has been conducted to show these effects (Jordan et al., 2010). In general, it is necessary and practical to operate away from slopes that may be subject to landslides and prepare a detailed terrain survey report that outlines the sensitive areas. Besides, helicopter or full-suspension yarding may cause less soil erosion than conventional cable yarding and research also reported the possibility of commonly applying helicopter-yarding and single tree selection to coastal forests harvesting (Millard & Floyd, 2010). Unlike coastal forest region where high precipitation (mostly rainfall) rates are common to all rainforests, Interior region has typically low rainfall intensities, and most runoff and erosion events occur during the snowmelt season. Forest operations conducted in this region include keeping soil disturbance below critical levels during logging, recontouring of skid trails following harvesting, leaving sufficient riparian buffers, and controlling erosion from logged areas in order to reduce sediment supply to stream networks (Jordan, 2006). Research in boreal forest watershed (Kreutzweiser et al., 2009) showed that logging impacts on stream sedimentation appeared to have been mitigated by careful logging practices including winter harvesting in riparian areas to reduce ground disturbance. Winter harvesting was also suggested as the best approach to prevent soil compaction (McLellan, 2014). Thereby, it also can be viewed as a good recommendation to implement best management practice in sub-boreal spruce regions (Interior plateau).

As mentioned before, small streams (common in coastal watersheds) which provide important ecosystem services, strongly influence downstream environments should need to be included in the discussion. Small streams refer to those channels that have no perennial tributaries to them, and themselves may be intermittent or seasonal in surface flow (Moore and Richardson 2003). As a unique ecosystem, small streams are strongly connected to their surroundings via sediment transportation, bank stability, water quality and nutrient dynamics and need more protection activities during and after logging than larger rivers (Richardson et al., 2010). BMPs for forestry activities near small streams must minimize physical damages to the stream channel, and stream crossings, road drainage patterns, road maintenance, and road deactivation are the four most critical concerns (Macdonald et al., 2003).

In order to reduce adverse impacts caused by forest harvesting, integrated mitigation measures should include both best riparian management strategies and careful logging activities. A sound riparian management plan should be prepared that address the riparian area across the entire forest land and watershed, preferably with the input and cooperation of adjacent landowners (Broadmeadow & Nisbet, 2004). High-quality roads and better maintenance are necessary to reduce sediment supply and control sediment delivery to streams (Slaymaker, 2000). Besides, new technologies (e.g. use of excavators instead of bulldozers for most construction) applied in the forest road construction can also effectively reduce sediment production from slope failures (Jordan et al., 2010). Nevertheless, quantitative researches still need to be conducted to compare different harvesting methods and provide forest management planner better suggestions to achieve both economic and environmental objectives. In general, a holistic approach is required to control sediment production (especially sediment supply) across different landscapes. What’s more, a better understanding of the interaction between sediment dynamics and forest harvesting and continuous implementation of best management practices will result in fewer problems.

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