Stream Crossing Inventories in the Swan and Notikewin River Basins of Northwest Alberta: Resolution at the Watershed Scale

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Abstract

Aquatic habitat fragmentation, degradation and encroachment resulting from industrial activities can alter the distribution, abundance and subsequent viability of stream fish populations. Using GIS tools and field assessments we documented crossings of streams by road networks and assessed their potential to fragment stream habitats and to act as sources of sediment intrusions into stream channels in two boreal watersheds in Alberta, Canada. Our data showed that the density of stream crossings in the Swan River watershed (0.24 crossings / linear stream km) was about three times higher than that in the Notikewin River watershed (0.068 crossings / linear stream km). Culverts were the predominant crossing structure in both basins and occurred predominantly on first to third order streams. Our field assessments suggest that the majority of culvert crossings in the Notikewin (61% of all crossings assessed) and Swan basins (74%) have the potential to fragment stream habitats. Culverts can obstruct fish passage through various processes. Undersized or improperly graded culverts can result in velocity barriers and cause downstream scouring, resulting in a perched culvert. Assuming that these structures impede fish passage, culvert barriers could result in limited access to about 20% and 9.5% of the total length of stream habitats in the Swan and Notikewin watersheds, respectively. Assessments also identified many culverts less than bankfull width that reduce the surface area of benthic habitats. From our qualitative assessments relatively few culverts in the Notikewin (17%) and Swan River watershed (18%) potentially contributed moderate levels of silt to stream channels. The propensity of culverts and bridges to potentially contribute high amounts of sediment to stream channels in the Swan (19% of all culverts; 36% of all

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bridges) was higher than that in the Notikewin River watershed (3% of all culverts; 8% of all bridges). Taken together, our preliminary assessments suggest that fragmentation of stream habitats and sedimentation related to development of road networks is an important management issue and that additional efforts are required to better understand the effects of stream crossings of stream fish communities in northern boreal systems.

Introduction

The development of road networks is an inevitable outcome of any land-based development activity and has been shown to impact watershed health (e.g., Haskins and Mayhood 1997). Stream crossings can cause both immediate and longer-term effects on fish populations primarily by modifying water quality, substratum composition and fragmenting stream channels (Adams and Whyte 1990; Toepfer et al. 1998; Eaglin and Hubert 1993). Connectivity of fish habitats is considered to be critical in conserving the distribution and abundance of stream fish assemblages (Rieman and McIntyre 1993), while reductions in connectivity impede fish movements and alter fish community structure and likely threaten population viability (e.g., Morita and Yokota 2002).

Expansion of industrial activities in Alberta's boreal forest and the concomitant development of road networks have raised questions about the sustainability of stream fish communities. Like elsewhere, the extent that road networks impact stream fish communities in boreal ecosystems of Canada are not well understood. This information is required to evaluate the need to develop: i) remedial actions and ii) alternative management practices.

The objectives of the present study were to describe the density, type and condition (i.e., fish passage and erosion potential) of stream crossings in two watersheds in the boreal forest of northwest Alberta. Specifically, we addressed the following questions: 1) What is the density of road crossings?, 2) What is the predominant road crossing structure?, 3) To what extent do road crossings affect stream habitat? Based on watershed morphometry, we predicted that culverts would be the dominant crossing type and that the likelihood of culverts to impede fish passage would be sufficiently high to have potentially detrimental effects on stream fish populations. We also expected that stream crossings would likely pose risks to stream fish mediated by sediment intrusions.

Methods

Study Area and fish communities

The study was conducted in the Notikewin and Swan River basins located in northwest Alberta, Canada. The Notikewin River Watershed is located northwest of Peace River and drains an area of 9,799 km^2. GIS layers derived from Indian Remote Sensing II Satellite imagery collected in 1998 showed that the watershed includes 1,665 km of permanent roads and a total of 544 road-stream intersections (i.e., stream crossings). The Swan River Watershed is located south of Lesser Slave Lake, drains an area 3,117 km^2 and from queries of GIS databases includes 3,931 km of permanent roads and 759 road-stream intersections.

Fish communities in the Swan River drainage are comprised of 11 species and are dominated by lake chub, longnose suckers and Arctic grayling (Unpublished data Fisheries Management Information System 2003) (Table 1). In contrast, fish communities in the Notikewin River drainage are comprised of seventeen species dominated by Arctic grayling, long nose sucker, lake chub, brook stickle back, trout-perch and northern pike (Scrimgeour et al. 2003b) (Table 1).

Identifying study sites

The location of potential stream crossing sites were derived from Geographic Information Systems (GIS) databases that were queried to identify intersections (i.e., stream crossings) between roads and the streams, based on a hydrologically-corrected stream layer. Site coordinates were further attributed with several unique identifiers to generate a list of stream crossing sites for field assessments. Additional sites we identified by field surveys and not GIS layers were included in the total number of crossings assessed. We attempted to survey all crossings identified by GIS in the Notikewin River Watershed. Using the Strahler stream ordering system, 406 of the 759 crossings identified in the Swan River Watershed, were located on first order streams. Occurrences of fish in first order streams in the Swan River Basin are extremely low (Authors unpublished data) and as a result were excluded from assessments.

Stream crossing assessments

Stream crossing assessments were conducted from

Table 1. Common and scientific names of fish recorded in the Notikewin and Swan River basins. The presence of spoonhead sculpin in the Notikewin Watershed may result from the misidentification of slimy sculpin. Fish data for the Notikewin River Basin were provided from Scrimgeour et al. (2003b).

Family and common name	Species	Watersheds	
		Notikewin	Swan
Cyprinidae			
Lake chub	*Couesius plumbeus* (Agassiz)	+	+
Flathead chub	*Platygobio gracilis* (Richardson)	+	-
Finescale dace	*Phoxinus neogaeus* Cope	+	-
Pearl dace	*Margariscus margarita* (Cope)	+	-
Longnose dace	*Rhinichthys cataractae* (Valienciennes)	+	-
Northern redbelly dace	*Phoxinus eos* (Cope)	+	-
Emerald shiner	*Notropis atherinoides* Rafinesque	+	+
Northern pikeminnow	*Ptychocheilus oregonensis* (Richardson)	-	-
Percopsidae			
Trout-perch	*Percopsis omiscomaycus* (Walbaum)	+	-
Gasterosteidae			
Brook stickleback	*Culaea inconstans* (Kirtland)	+	+
Percidae			
Walleye	*Stizostedion vitreum vitreum* (Mitchill)	+	+
Salmonidae			
Arctic grayling	*Thymallus arcticus* (Pallas)	+	+
Mountain whitefish	*Prosopium williamsoni* (Girard)	+	+
Rainbow trout	*Oncorhynchus mykiss* (Walbaum)		+
Bull trout	*Salvelinus confluentus* (Suckley)	-	-
Esocidae			
Northern pike	*Esox lucius Linnaeus*	+	+
Catostomidae			
Longnose sucker	*Catostomus catostomus* (Lacepède)	+	+
White sucker	*Catostomus commersoni* (Forster)	+	+
Cottidae			
Slimy sculpin	*Cottus cognatus* Richardson	+	+
Spoonhead sculpin	*Cottus ricei* (Nelson)	+	-

June through August in 2002. Assessments were designed to document crossing type and condition, and to provide a rapid assessment of the potential risk to impede fish passage and to contribute sediments to the stream channel in both watersheds.

Identification of crossing types. We identified the four crossing types of culverts, bridges, fords, and decommissioned crossings. Decommissioned crossings were defined as locations where a crossing structure had been installed and subsequently removed. These practices alter channel width and depth, substratum size composition and are often associated with high sediment inputs. Culverts (predominantly corrugated metal pipes) and bridges were further categorized by type and shape (e.g., Bridge/Bailey type). Cross-ditch drains and crossings on intermittent streams were not evaluated.

Stream and culvert properties - Replicate measures of rooted width (bank-full width ±1cm) were taken at least 25 m upstream of the crossing to avoid influence of the culvert on channel morphology. This measure was used to calculate encroachment ratios and habitat loss caused by encroachment defined by Harper and Quigley (2000). Culvert diameters (± 1cm) were measured on round (diameter) and elliptical, oval or box culverts as the widest distance across the culvert opening. Inadequately sized culverts encroach on fish habitat, constrict stream flow, increase velocities and may cause sedimentation and excessive scouring at the outlet (Parker 2000). Culvert outfall drop (±1 cm)

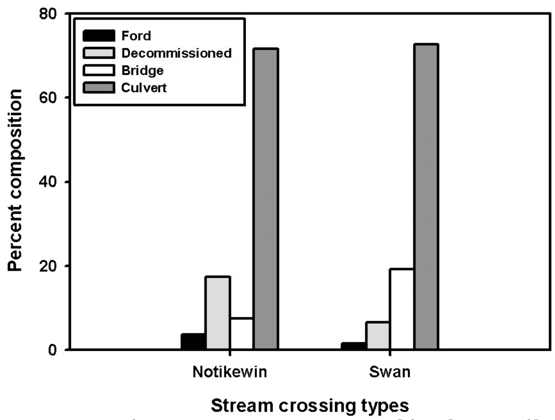

Figure 1. Crossing structures assessed in the Notikewin and Swan River basins in Northern Alberta, Canada. Ford = vehicular crossing bisecting the stream channel with no built up structure. Decommissioned = a crossing that was previously installed and has since been removed. Bridge = a structure placed above the stream channel typically spanning the bank-full width with or without in-stream abutments. Culvert = in-stream structure can be made of steel, concrete, plastic in round, half round, elliptical, or box shapes.

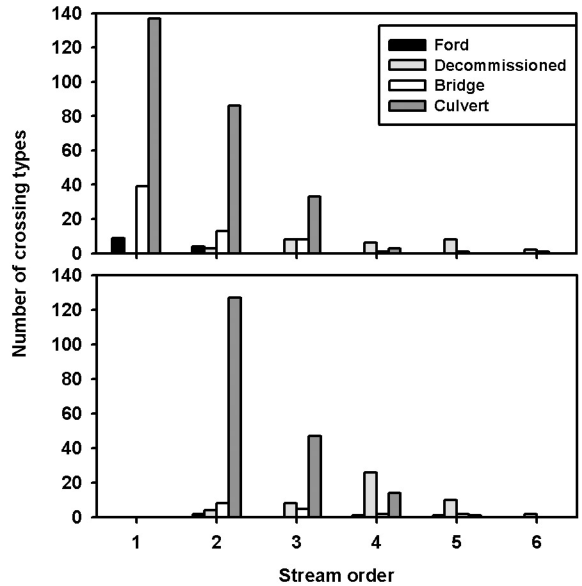

Figure 2. Number of crossing types as ford, bridge, decommissioned and culvert crossings in the Notikewin and Swan River watersheds, Alberta, Canada.

was measured as the distance from the bottom of the culvert outlet to stream water surface. Outfall heights exceeding 5 cm were considered to represent potential physical barriers to fish movements. Certain life stages of fish species may be unable to enter culverts that are set above the substrate [(e.g., slimy sculpin (*Cottus cognatus*)].

Sediment source assessments - The potential for sediment inputs to stream channels was evaluated visually by quantifying the potential for erosion of adjacent rights-of-way on the stream channel. Sites were assigned a rank of low, moderate or high potential for sedimentation based on evidence of: i) physically unstable river banks (i.e., evidence of slumping) at the site or immediately downstream of the site, ii) presence of non-vegetated soils or those with minimal vegetative cover, and iii) the absence or failure of sediment control structures to control sediment inputs. Our initial observations showed that bridges in both the Swan and Notikewin watersheds pose minimal risk of habitat fragmentation. As a result, we restricted our evaluation of the impacts of bridges on stream fish to those resulting from sediment inputs as previously described for culverts.

Photographic records - We obtained a photographic record of all crossings using a digital camera to document crossing condition and the condition of the adjacent rights-of-way (ROW). Digital photos were taken of the inlet, outlet and the two Rights of Way having the highest erosion potential. Lastly, our assessments also involved written documentation of other aspects of the crossing related to erosion potential and potential for fish passage.

Results

Data bases

Queries of GIS road and stream network layers identified a total of 544 intersections (i.e., potential stream crossings) in the Notikewin River Watershed and 759 intersections in the Swan River Watershed. Subsequent assessments indicated that 105 stream crossings (61 in Notikewin River Watershed and 44 in Swan River Watershed) were located in remote locations that precluded vehicular access and were not included in our assessments. Further assessments showed the presence of moderate numbers of stream crossings where water flow was either absent or insufficient to support fish communities. Using the Strahler stream ordering approach (Strahler 1964), the majority (406 of the 759) of stream crossings in the

Swan River Basin were located on first order streams. Because relatively few first order streams in the Swan Watershed support fish, data from first order systems were excluded from analyses (Tchir unpublished data). As a result, our assessments of crossing types and their potential to fragment stream habitats or result in sediment inputs were based on 413 and 352 road crossings in the Notikewin River and the Swan River watersheds, respectively.

Stream crossing density and structure types

Density of roads in the Notikewin Watershed (0.21 km of roads / watershed area km^2) was markedly lower and concentrated mainly in one sub-basin, compared to that in the Swan River Watershed (1.26 km roads / watershed area km^2). Similarly, in the Swan River Basin density of stream crossings (0.24 crossings / linear km) was more than three times higher than densities in the Notikewin River Watershed (0.068 crossings / linear km).

Culverts were the predominant stream crossing structure in both watersheds and were most prevalent on small streams (i.e., 1^{st}, 2^{nd} and 3^{rd} order streams) (Figures 1 and 2). Bridges were prevalent on third order streams and larger and were the only structure present on sixth order streams in both watersheds. Fords were observed exclusively on 1^{st} and 2^{nd} order streams in the Notikewin River Watershed, where as, fords in the Swan River Watershed were found on 2^{nd}, 4^{th} and 5^{th} order streams. In general, fords were located on reclaimed roads. While decommissioned crossings were observed on 1^{st} to 6^{th} order streams (Figures 1 and 2) in the Notikewin River Watershed, they were most prevalent on 1^{st} order streams. In the Swan River Watershed, decommissioned crossings occurred most frequently on 2^{nd} order streams and were located predominantly on deactivated and winter roads.

Multiple culverts were observed where previous culverts had apparently failed or where single culverts appeared to be insufficient to handle peak flows. Single and multiple steel pipe culverts (i.e., non-corrugated metal pipes) were rare and due to their condition were likely installed before the 1990s. The number of single and multiple culverts generally decreased with increasing stream order. Evidence of beaver activity was found at 35% and 16% of culvert crossings analyzed in the Notikewin River and Swan River watersheds, respectively.

Encroachment and habitat loss

The diameter of culverts was significantly less than bank-full measured at least 25 m upstream of crossings in the Notikewin (Paired t-tests: $t = 5.3$, df 111, $p < 0.005$) and Swan River Basin ($t = 4.4$, df 104, $p < 0.005$) and results in a reduction of the surface area of benthic habitats. The majority of culverts in both watersheds resulted in encroachment into stream channels (Notikewin River Watershed 69.9%, Swan River Watershed 83.7%). Crossing sites comprised of multiple culverts also resulted in habitat encroachment (Notikewin River Watershed 43.8%, Swan River Watershed 65.6%). There was a significant difference in the cumulative span of multiple culverts and bank-full width in the Swan River Watershed (Paired t-test: $t = 3.7$, df 68, $p < 0.005$) but not in the Notikewin River Watershed (Paired t-test, $t = 1.5$, df 15, $p > 0.05$).

Stream barriers and fragmentation

Based on our criteria, initial assessments showed that the majority of culvert crossings in the Notikewin (61% of all crossings assessed) and the Swan River watersheds (74% of all crossings assessed) likely impede fish movement and thus are potential barriers (Figure 3). Culverts with low water levels were typically, however, not considered to impede fish movement in either watershed. Barriers resulted from accumulations of organic debris at the inflow of culverts (i.e., debris blockages) and where flow from the bottom of the culvert is located above the water surface of the stream (i.e., a hanging culvert). Hanging culverts were the dominant cause of habitat fragmentation in both watersheds (Figure 3). Mean culvert outfall heights ranged from 26 –32 cm in the Notikewin and 19-67 cm in the Swan River Basin (Figure 4). However, inadequate culvert sizing and placement also caused debris blockages. Barriers caused by damaged inlets or outlets (i.e., damaged pipe) of culverts were uncommon in both watersheds.

If our assessment of what constitutes a barrier to fish movement is correct, our calculations suggest that fish populations may not be able to readily access about 20% of the headwater areas of the Swan River and 10% of headwater areas in the Notikewin Watershed. Because hanging culverts were identified to be the primary cause of potential impediments to fish movement, they also accounted for the majority of areas that are likely not freely accessible in both study watersheds.

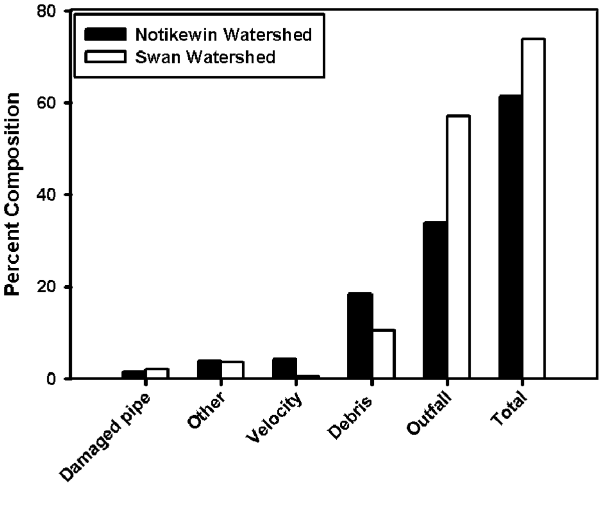

Figure 3. Percent composition of the dominant types of potential barriers to fish passage in the Notikewin and Swan River watersheds. Barriers due to damaged pipe occur as a result of physical damage of inflows and outflows of the culverts. The Other culvert barrier type includes beaver control structures (e.g., metal screens) at culvert inlets, hanging inlets, submerged culverts and agricultural modifications. Total represents the proportion of all culverts that were potential barriers to fish movement. Data are based on 362 and 260 road crossings in the Notikewin and Swan watersheds, respectively.

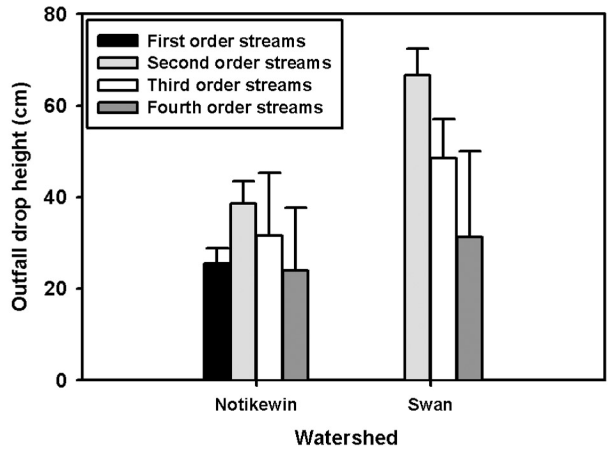

Figure 4. Mean (± SE) outfall drop height of culverts from first to fourth order streams in the Notikewin River Basin and second to fourth order streams in the Swan River Basin, Alberta, Canada.

Potential erosion

Our visual and qualitative assessments of erosion potential from crossing structures showed that 17% and 18%, respectively, of crossings in Notikewin and Swan River watersheds, likely contributed moderate levels of sediments to watercourses (Table 2). The propensity of culverts to contribute sediments was greatest in the Swan River Watershed (19%) compared to the Notikewin River Watershed (3%). In the Swan River Watershed, proportionately more bridges were rated as having high levels of silt deposition (Notikewin River Watershed 8%, Swan River Watershed 36%) (Table 2).

Discussion

We completed an environmental scoping exercise to evaluate the potential effects of road networks on stream fish communities inhabiting two boreal forest watersheds by quantifying their potential to impede fish movement and to reduce habitat quality by contributing sediments to stream channels. Our analyses identified culverts as the primary stream crossing structure in both watersheds and that the majority of culverts likely impede fish passage either because: i) water stage at culvert outflows was typically located above the water surface or ii) the presence of accumulations of debris at culvert inflows. In fact, mean culvert outfall heights ranged from 26 –32 cm in the Notikewin and 19-67 cm in the Swan River Basin. Our assessments also suggested that road networks and related stream crossings could impact fish assemblages by contributing sediment from road approaches ands rights-of-way that were physically unstable or poorly vegetated. Taken together, our preliminary assessment suggests that road networks in the two basins have the potential to impact stream fish communities. We suggest that additional efforts are required to more fully evaluate threats to stream fish communities in these basins and should include an evaluation of remedial actions to reduce crossings that likely severely restrict fish passage.

Our suggestion that road networks may potentially impact stream fish communities is not new. In fact, concerns about poorly designed roads and stream crossing structures have been expressed for at least two decades (Everest and Harr 1982; Adams et al. 1986; Furniss et al 1991; Weaver et al. 1987), while several recent studies have demonstrated negative effects of roads and associated stream crossings on stream fish populations (e.g., Beechie et al. 1994; Conroy 1997;

Table 2. Number of crossings rated as contributing moderate and high levels of sediments to streams in the Notikewin and Swan River watersheds. Decom. = Decommissioned stream crossings. Stream crossings on first order streams were not evaluated.

Notikewin	Bridge	Culvert	Ford	Decom.
Stream Order				
1	0	35	3	7
2	0	12	1	0
3	4	10	0	3
4	1	0	0	1
5	4	0	0	0
Unknown	0	8	0	0
Total	9	65	4	11
Swan	**Bridge**	**Culvert**	**Ford**	**Decom.**
Stream Order				
1	-	-	-	-
2	1	45	0	2
3	5	24	0	1
4	19	7	0	0
5	9	1	0	0
Unknown	1	0	0	0
Total	36	77	0	3

Pess et al. 1998). Additional concerns have also been raised about the ability of structures to provide fish passage under variable flow conditions (Ashton and Carlson 1984; Bates et al. 1999). Our observation that the majority of culverts in the Notikewin and Swan River basins likely impede fish movement is in part, a consequence of management practices in the 1970's and 1980's. During this period, culverts were designed and installed primarily to provide a stable and cost-effective water control structure capable of supporting vehicle use. Additional considerations of how different culvert designs and installation practices could fulfil these requirements, while not impeding fish passage, are a relatively recent advancement. In Alberta, this paradigm shift coincided with the rapid expansion of the forest sector in the early 1990's and the continued expansion of the oil and gas sector. While not quantified, our observations in both watersheds suggested that many, but not all, culverts that likely restrict fish passage appear to result from older structures.

Installation of under-sized culverts and those that are not embedded in the streambed are more likely to fragment stream fish habitat than alternate practices. Undersized culverts have been shown to increase the likelihood of habitat fragmentation resulting from water stage at outfalls being above the water surface and because of high water volumes and velocity exceeding swimming capabilities (i.e., velocity barriers). Non-embedded structures (i.e., culvert installed above the stream channel) can result in substrate scouring (i.e., removal of sub grade material) and in dewatering and erosion of stream habitat immediately downstream of the culvert outfalls (Harper and Quigley 2000). Our data suggest that culvert crossings were more severely undersized in the Swan River Watershed than that in the Notikewin River Watershed. As a result, we expect that the potential risk of habitat fragmentation in the Swan exceeds that in the Notikewin River Basin.

Efforts to minimize negative impacts of culverts on stream fish communities has focussed largely on understanding the ability of fish to: i) access culvert outfalls that are located above the water surface and ii) navigate high gradient and often hydraulically complex flow (e.g., Behlke 1991; Furniss et al. 1991). These sources of information have resulted in the development of guidelines related to preferred heights of culvert outfalls and design considerations related to culvert size, length, slope and in-culvert structures (e.g., baffles) that allow fish passage (refs here). While these studies have enhanced the ability of some species of fish to access and navigate culverts, effects of culverts on stream fish assemblages at the watershed-scale remain poorly understood. For instance, swimming abilities of many non-salmonids are poorly known; as are the cumulative energetic costs of navigating series of poorly designed or installed culverts. Despite these and other information deficiencies, our observations in the Notikewin and Swan River basins suggest that many of the concerns related to impeding fish passage may be alleviated by installing appropriately sized open or oval culvert designs that are set into, rather than above, the stream beds. In addition, increased focus on restoring vegetation cover to approaches to culverts and ROW may also dramatically reduce the number of stream crossings that potentially can contribute sediments to stream.

Our data suggested that the majority of concerns related to sediment inputs to stream originated from: i) physically unstable soils (i.e., where evidence of mass slumping was apparent), ii) poorly vegetated areas located immediately adjacent to stream crossing structures and within stream banks rights-of-ways and iii) bridge surfaces with large gaps between bridge materials that allow sediments on the bridges to fall into stream channels. Our observations also suggest that deactivated stream crossings in both watersheds surveyed were typically poorly vegetated and seldom associated with sediment control structures or if present were likely ineffective in minimizing sediment inputs to streams.

Although bridges were not analyzed for encroachment in this particular study, Harper and Quigley (2000) found bridges with shorter spans had a larger ecological footprint as a result of the adjacency of bridge abutments to the stream channel. These structures required extensive riprap to prevent substratum scour protection and resulted in increased habitat losses due to encroachment. They also suggested that bridges with longer spans were found to require less riprap and resulted in minimal disturbance of the stream banks (Harper and Quigley 2000). Eaglin and Hubert (1993) suggested that sediment delivery to streams might be positively related to the number of stream crossings. They found that the extent that large substrata were embedded in fine sediments increased with the number of stream crossings whereas the abundance of cobble substrates decreased with number of stream crossings. Cross-ditches with deeply rooted and abundant vegetation combined with sediment control structures (i.e., traps) can reduce the supply of sediments form road, ditches, and ROW to streams.

Restoring connectivity of watercourses has been contended to be an effective way to increase the availability of productive fish habitat. Roni et al. (2001) reported that the relative benefits of restoring fish passage can exceed those attained from development of off-channel habitats, instream structures and sediment reduction activities. Other studies have reported that removal of physical barriers can increase the abundance of parr, juvenile and adult salmonids (e.g., Beechie et al. 1998; Pess et al. 1998). Given that replacement and repair of culverts and other stream crossing structures can result in sediment input and alteration of instream fish habitat to some extent, and can be extremely costly, we urge resource managers to carefully consider where replacement and repair efforts are most appropriate. For example, we recommend that resource managers evaluate the quantity and quality of stream habitat upstream of crossings that impeded fish movements before they recommend any remedial activities.

Our data identified moderately high numbers of stream crossings in the Swan River Basin. In fact, our data showed that roads on average intersected streams at 4 km intervals and that the total number of stream crossings by seismic lines, power ROW, rail lines and small trails not identified in existing GIS layers are likely substantially higher. Our previous studies in two other boreal forest watersheds in northern Alberta have shown that stream crossings by roads comprise only 25-40% of all stream crossings (Scrimgeour et al. 2003a). The ecological consequences of high numbers of stream crossings on fish communities within Alberta's boreal forest and the mechanisms through which they are mediated are poorly understood.

We suggest that an improved understanding of the effects of road networks on stream fish within Alberta's boreal is required to ensure that industrial development activities can occur without compromising stream ecosystems. Broad research needs are required to provide an improved understanding of: i) landscape-level patterns in road networks and how they are progressing throughout the boreal forest, ii) current and forecasted effects of road networks on multiple life history stages (Toepfer et al. 1998) and migratory and non-migratory stream fish communities, iii) the extent that stream fish populations function as metapopulations (Riemen and McIntyre 1993; Morita and Yokota 2002) and iv) cost-effective remedial plans to reduce current impacts.

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