University of Alberta

Stream fragmentation by hanging culverts along industrial roads in Alberta's boreal forest: assessment and alternative strategies

by

David James Park ©

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Your file Votre référence
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For Connor,

whom I hope never has a fishing trip interrupted by a hanging culvert

Abstract

Culverts are commonly installed wherever roads cross small streams. Hanging culverts, those with elevated outfalls, are upstream movement barriers for fishes and cause watershed fragmentation. Half (50%) of industrial road culverts surveyed in four northern Alberta watersheds were hanging. Hanging culverts developed over time, at a rate regulated by landscape gradient. I developed HANGFRAG, a simulation model to compare stream fragmentation and infrastructure costs resulting from alternate road management strategies for simulated high and low gradient watersheds, at high and low levels of initial road development, for low and high degrees of management intervention. In both areas, low intervention was achieved cost-effectively by hanging culvert replacement, combined with road build rate reduction and stream crossing avoidance. For high intervention, greatest cost-effectiveness was achieved through the alternative use of temporary bridges, more so in steep landscapes. I placed watershed fragmentation in the context of island biogeography theory and constructed a conceptual watershed-scale strategic planning model for remediation of fragmentation.

Acknowledgements

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Chapter 1 – Introduction

Habitat fragmentation, or the subdivision of once continuous areas of habitat into smaller discontinuous patches, has been implicated as a primary threat to species persistence and ecological integrity of ecosystems throughout the world (Harris 1984; Wilcove et al. 1986; Saunders et al. 1991). Generally, smaller habitat patches support smaller numbers of individuals than larger patches, which increases the probability that stochastic events will cause local extinctions in small patches (Shaffer 1981; Lande 1988). Creation of a hostile landscape matrix via habitat fragmentation reduces migration rates among habitat patches, decreasing rates of colonization of vacant habitat patches (Hanksi and Gilpin 1991). Habitat fragmentation has genetic consequences as well. Reduced local population sizes and movement in fragmented landscapes can lead to increased levels of inbreeding and decreased genetic diversity within subpopulations, increased differentiation between subpopulations, and reduced effective population sizes in the larger metapopulation (Charlesworth and Charlesworth 1987; Hedrick and Gilpin 1996; Monaghan et al. 2002). The loss of genetic diversity can further reduce the ability of a species to adapt to environmental changes (Lande and Barrowclough 1987). Combined, the environmental and genetic effects of habitat fragmentation can accelerate the decline and extinction of species (Gilpin and Soule 1986; Lande 1988; Saccheri et al. 1998).

Habitat fragmentation may be a key factor reducing the long-term sustainability of species reliant on lotic aquatic systems (Zwick 1992; Labbe and Fausch 1999; Reiman and Allendorf 2001; Pringle 2003). Fragmentation of lotic habitats is a particularly serious concern for aquatic species that require access to entire river networks to complete their life cycle (Tack 1980; Hughes 1999; Stanislawski 1997; Schmetterling and Adams 2004). As movements of many stream-dwelling organisms such as fishes are limited to within watercourses, in-stream movement barriers can isolate populations, forming smaller sub-populations each with a higher risk of local extinction (Morita and Yamamoto 2002). This risk may be particularly acute in environments where temporal variability in habitat quality is large (i.e. annual winterkill in fishes). While such events exist within the range of natural variability, when individuals cannot access refugia to escape adverse conditions, localized extirpations are more likely to occur. If immigration into depopulated areas is blocked, fragmented habitats are effectively lost as habitat and this loss may potentially be permanent. Over time, localized losses of available habitat accumulate and substantive changes in the size of the overall metapopulation will become detectable at larger and larger spatial scales. The persistence of fish and other aquatic organisms in landscapes driven by natural disturbances may depend on their ability to move with minimal constraint.

In lotic ecosystems, anthropogenic fragmentation of habitat typically occurs from flow diversions and flow abstractions that create reaches of discontinuous flow interspersed with reaches of flowing water, and the installation of structures such as dams that are barriers to the movement of organisms (Zwick 1992; Dynesius and Nillson 1994; Rosenberg et al. 2000). Road development, with commensurate installation of stream crossing structures, is a major source of lotic fragmentation (Warren and Pardew 1998; Harper and Quigley 2000; Angermeier et al. 2004). Culverts, commonly used where roads cross small streams, may act as barriers to organism movement, particularly upstream, and thereby cause fragmentation of habitats and populations (Anderson and Bryant 1980; Baker and Votapka 1990; Furniss et al. 1991). The mechanisms by which this occurs include: a) water velocity and culvert length exceeding the swimming performance of fishes, b) insufficient depth of water in the culvert, c) excessive turbulence below the culvert, and d) the outfall elevation of the pipe may be too high, exceeding the jumping ability of fish (Furniss et al. 1991). This latter condition, known as a "hanging" or "perched" culvert, may arise either as a result of poor installation practices or may form over time as a consequence of flow-induced scouring of the stream bed immediately below the outlet. Hanging culverts are of particular concern for ecologists and aquatic resource managers, as they persist and worsen over time unless the structures are replaced or removed (Furniss et al. 1991).

The nature of lotic environments in Alberta's boreal forest makes species reliant on such habitats particularly sensitive to fragmentation. Boreal watersheds are strongly influenced by large-scale events, such as extended periods of ice cover and periodic drought (Schneider 2002). Small, low order streams are generally influenced by disturbances to a greater degree, and species in small streams are thus profoundly affected by these conditions. Populations of organisms such as fishes, persisting in boreal watersheds have adapted by either being tolerant of adverse conditions, as is the case with brook stickleback (*Culea inconstans*) (Nelson and Paetz 1992), or displaying high mobility, exemplified by the often-extensive seasonal movement patterns of Arctic grayling (*Thymallus arcticus*) (Tack 1980, Tripp and Tsui 1980, Hughes 1999, Stanislawski 1997). Despite such adaptations, the ability of boreal fishes and other organisms to persist in inherently dynamic boreal lotic habitats could be impaired by road-induced fragmentation (Angermeier et al. 2004).

Alberta's rapidly developing road network and culvert system is cause for concern for those interested in maintenance of aquatic biodiversity in the boreal forest

(Tchir et al. 2004). Industrial development requires road development, and much road building is occurring in Alberta's boreal forest as a result of forestry and petrochemical industrial activities. Road densities in some locations in northern Alberta are at or near what may be the practical maximum (5 to 6 km/km^2), at which point access needs are arguably fully met. In less developed areas, projections based on reviews of corporate and government business plans suggest that much of the boreal forest will reach this maximum within 50 years (Schneider 2002). In Alberta, fish passage requirements are mandatory for all road crossings on sport fish-bearing streams and road builders are required to install and maintain culverts that meet these regulations. The business-as-usual (BAU) approach to culvert management associated with road building is site-specific. Culvert placement and size are dictated by average predicted stream discharge and the ability of the adult sport fish present within a stream to use a particular culvert arrangement under average conditions (DFO 1986;Government of Alberta 2002). Whether culverts designed for "average" conditions for sport fish are sufficient to maintain lotic biodiversity is unknown. Recently, regulations have changed to include consideration of non-sport fish movement, but the number of culverts installed prior to the adoption of these regulations is considerable (Tchir et al. 2004). Furthermore, there is a perception among many that the maintenance of Alberta's culvert system is inadequate and that a large backlog of culverts exist that fail to meet even sport fish standards. Despite these concerns, no studies regarding the overall cumulative effects of culvert-related fragmentation on boreal stream networks and biological integrity exist.

Strategic, landscape-level questions about the cumulative effects of lotic fragmentation caused by hanging culverts need to be addressed. To do this, current rates and degrees of fragmentation should be quantified and related to factors measurable at local and landscape extents. Expected fragmentation rates in representative situations can then be developed to serve as benchmarks against which alternative trajectories can be assessed. From these efforts, alternative strategies can be developed as best management practices (BMP's) that achieve desired results.

In this thesis, I identify and present alternative strategies that represent best management practices to reduce the fragmentation effects of hanging culverts in a landscape predicted to undergo continued high levels of industrial road development. In chapter 2, I present the results of a retrospective study designed to quantify the occurrence, age, and characteristics of hanging culverts and their physical setting along industrial roads in four study areas located in northern Alberta. I then test for and describe relationships between hanging culvert occurrence and various landscape and culvert-specific factors. I also quantify the amount of lotic habitat fragmentation caused by hanging culverts in my study areas.

In chapter 3, I use data from the second chapter to develop spatial relationships between streams, roads, and stream crossings using empirical and simulated spatial data and then develop an aspatial simulation model that uses the parameters from chapter 2 to examine how a developing industrial landbase with an increasing road footprint fragments lotic systems in different natural conditions. Using the model, I then describe the landscape-level cumulative effects of hanging culverts on simulated boreal watersheds and conduct scenario analyses to assess the relative effectiveness of alternate stream-crossing and road management strategies, with the goal of identifying new best management practices.

In the last two chapters, I put this study into a broader ecological and resource management perspective. In chapter 4, I discuss the ecological implications of fragmentation of boreal watersheds and explore a conceptual framework for understanding fragmented stream reaches in the context of island biogeography theory. Based on this framework, I present a conceptual model for strategic planning of remediation of fragmentation at the watershed scale. Finally, in the summary, I highlight some key points and present recommendations for future research.

Chapter 2 – Assessment of factors affecting the occurrence of hanging culverts along industrial roads and lotic fragmentation in Alberta's boreal forest

Introduction

Poorly installed culverts or those that become movement barriers over time are agents of fragmentation for aquatic species occupying lotic environments (Furniss et al. 1991, Warren and Pardew 1998, Harper and Quigley 2000, Gibson et al. 2005). Culverts are especially serious impediments to movement of fishes, particularly upstream, when they have outfalls that are elevated above the water surface (aka hanging culvert). Once this condition arises, it persists until the culvert is replaced or removed, although outfall hang height will vary with fluctuating stream flows or water elevation.

Mechanistic aspects of culvert crossings by aquatic organisms have been extensively studied. Considerable work has been done to determine proper design and installation criteria and develop regulations that minimize impacts on fishes (see review by Moore et al. 1999). Resource management agencies typically have clear regulations regarding culvert design and installation, particularly on watercourses bearing populations of sport fishes. In Alberta, fish passage requirements are mandatory for all road crossings on sport fish-bearing streams (Government of Alberta 2002) and road builders are required to install and maintain culverts that meet these regulations.

Despite our general knowledge of culverts and the negative ecological effects of improperly designed, installed and maintained culverts on fish, hanging culverts do exist in Alberta and strategic landscape-level issues have emerged. Questions about the degree and cumulative effects of lotic fragmentation caused by hanging culverts at large landscape scales have not been adequately addressed. In particular, there is a paucity of information on how culvert design, age and physiographic characteristics of watersheds and individual streams influence the propensity of culverts to become hanging and the degree to which hanging culverts fragment stream networks at larger spatial scales. Development of landscape level models of the effects of road management strategies on stream fragmentation over time, and subsequent best management strategies requires such information.

Following this need, the first two objectives of this chapter are to: i) quantify the occurrence, magnitude, and age-structure of hanging culverts along industrial roads in four study areas in Alberta; and ii) test for and describe relationships between the occurrence of hanging culverts, culvert age, culvert diameter and attributes of its physical setting. My third objective is to quantify the amount of lotic habitat fragmentation caused by hanging culverts in my study areas. Understanding why and when a particular culvert hangs is crucial to the sustainable management of lotic systems. However, to assess whether culverts fragment lotic systems, the effect of individual culverts must be rationalized in a biological context and then accounted for at larger spatial scales. I argue that hanging culverts function as one-way biological flow regulators, impeding movement of fishes to upstream habitats. The amount of lotic habitat fragmented and the nature of resulting fragments therefore depend on barrier location. Knowing hanging culvert locations and stream order at the site of the barrier potentially facilitates the measurement of hanging culvert fragmentation at a watershed scale.

Study Areas

Data were obtained from surveys conducted within four watersheds in northern Alberta (Figure 2.1) within the Peace River Basin. Whereas the bounds of the Swan and

Notikewin River study areas correspond to their watershed boundaries, the boundaries of the Calling and Christina areas do not, being arbitrarily set within the Calling and Christina river watersheds, owing to the differing data collection objectives (see Methods). Study areas represent an array of topographies and varying intensity of industrial activity (Table 2.1). Oil and gas extraction, seismographic exploration and timber harvesting are the dominant industrial activities in all areas.

Periods of drought are not uncommon in northern Alberta, the most recent of which occurred just prior to the 2002-2003 survey period (Environment Canada 2004). During these years, flows in streams in focal watersheds were at or near recorded lows. In the Swan and Notikewin river watersheds, regional stream flows were recovering but still below the 30 to 40 year average recorded by Environment Canada monitoring stations (Water Survey of Canada 2004). Flows in the Calling River and Christina River watersheds were at or above average.

All four areas support relatively diverse fish communities for northern Alberta. Northern pike (*Esox lucius),* Arctic grayling (*Thymallus arcticus),* walleye (*Sander vitreus),* brook stickleback (*Culaea inconstans),* lake chub (*Couesius plumbeus),* longnose sucker (*Catostomus catostomus)* and white sucker (*Catostomus commersonii)* occur in all areas.

Table 2.1. Characteristics of the four study watersheds located in central-north Alberta. Information derived from Strong and Legatt (1992), Environment Canada (2004) and Tchir et al. (2004). Road lengths were calculated using spatial data collected in 2000. m ASL = meters above average sea level.

Area	Size (km^2)	Dominant ecoregion	Dominant soils	Dominant tree species	Mean summer air temperature (°C)	Mean summer precipitation (mm)	Mean annual precipitation (mm)	Maximum elevation (m ASL)	Total industrial road length (km) and density (km/km^2)
Swan River watershed	3,117	Upper Boreal Cordilleran	Brunisols, Gray luvisols	lodgepole pine (*Pinus contorta)* white spruce *(Picea glauca)*	11	340	503	1350	1278 (0.41)
Notikewin River watershed	9,799	Lower Boreal Cordilleran	Brunisols, Gray luvisols	aspen poplar *(Populus tremuloides)* white spruce black spruce *(Picea mariana)*	13	295	391	1085	1077 (0.11)
Calling area	2,179	Lower Boreal Cordilleran	Brunisols, Gray luvisols	aspen poplar balsam poplar *(Populus balsamifera)*	13	295	453	941	695 (0.32)
Christina area	6,831	High Boreal Mixedwood	Gray luvisols, Dystric brunisols	aspen poplar balsam poplar	12	265	455	774	1752 (0.11)

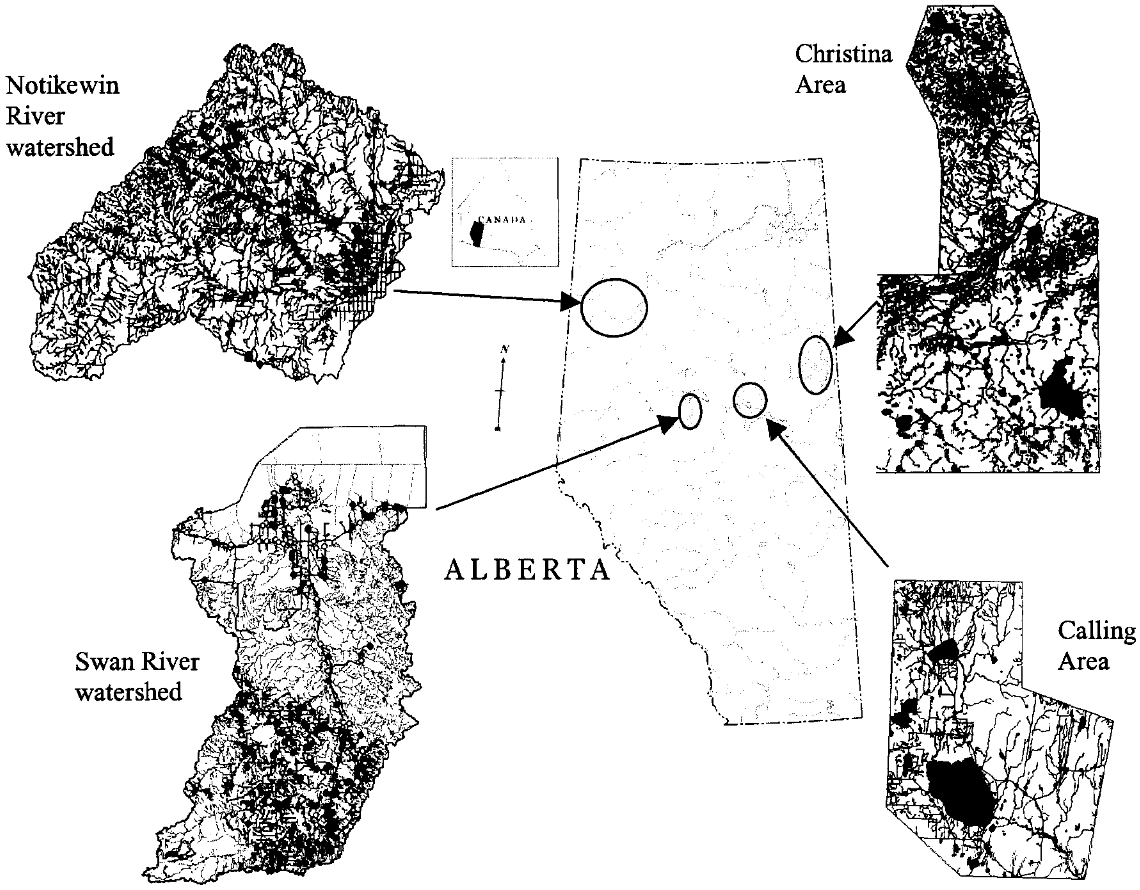

Figure 2.1. Map showing locations of culvert study areas in northern Alberta, 2002-2003. Red dots indicate culvert locations.

Methods

Survey Design and Site Selection

Field surveys in northeast Alberta (Calling and Christina areas) were coordinated with other stream crossing survey efforts in northern Alberta to increase the amount and scope of information available. Although data were collected in a similar and compatible fashion, survey objectives differed somewhat, and the differences influenced the delineation of study area bounds and amount of data collected. The Alberta Conservation Association (ACA) conducted surveys in 2002 of the Swan and Notikewin river watersheds to inventory all stream crossings (Tchir et al. 2004). During the surveys I conducted in the Calling and Christina areas in 2003, my objective was to survey, but not inventory, only culvert crossings located within the Forest Management Area held by Alberta-Pacific Forest Products Incorporated.

In all areas, candidate survey sites were identified using ArcView 3.2 (ESRI 2000) depictions of spatially correct hydrographic and road network Global Information System (GIS) data layers obtained from the Alberta Government. Accessible sites were subsequently located in the field using map depictions of spatial data layers and a handheld Global Positioning System (GPS) receiver, and classified according to crossing type (e.g. ford, bridge, culvert), watercourse presence and type (e.g. defined natural watercourse vs. drainage ditch or canal), and road type (e.g. no road, winter, dry-weather, all-weather, paved). No crossings of first order watercourses were surveyed in the Swan River watershed, based on observations that such watercourses were ephemeral and often dry (Tchir et al. 2004). This was not the case in the other three areas. Only industrial roads were examined and these were defined as those not part of a municipal or provincial public road network. No attempt was made to avoid surveys of multiple crossings that were associated with the same road or stream.

Culvert Attributes

Surveys of culverts in all areas were completed in similar fashion, following protocols described by Tchir et al. (2004) and based on those previously described by Parker (2000), Furniss et al. (1998) and Harper and Quigley (2000). I defined a culvert as hanging if the lowest edge of the outfall of the pipe was > 1 cm above the water surface at the time of survey. This dimension was measured to the nearest centimeter (cm) and is referred to as culvert hang height. Culvert crossings occasionally consisted of vertically offset pipes, in which the uppermost culvert only receives flow during high periods of discharge. If more than one culvert was present at a site, measurements of all culverts were taken. However, at sites with multiple culverts I analyzed hang height only for the lowest culvert. All measurements were made (+/-1cm) using either a 1-meter measuring rod or 30 meter measuring tape.

Culvert age (C_AGE) was estimated by examining aerial photography. I combined this with any evidence from field assessments to evaluate whether culverts had been replaced following initial installation. The absence of databases documenting culvert installation date precluded direct measurement of culvert age. Photographic evidence of the first appearance of developed roadbeds on the landscape was deemed to be the most definitive means available to determine road-crossing and culvert age. Road age, to year, was determined using images archived by the Government of Alberta. Most photographs were black and white and were between 1:15,000 and 1:30,000 scales. Annual photographic series were reviewed to determine year of road development.

Photographs were generally available from 1949 to present, with gaps in annual coverage of varying degree (1 to 15 years). Gaps were generally larger between older (> age 25) photo series. Culvert age was assumed to be the year of roadbed development. In the majority of cases, road and culvert dates were narrowed down to a single year. In cases where road date could not be resolved to this level of accuracy, the designated year was set as the middle of the range of uncertainty, unless prior knowledge or other information suggested it be shifted. The potential error of ageing was assessed by calculating the percentage of the range of uncertainty (time span) of the estimated age of the culvert.

This method of quantifying culvert age was not capable of assigning correct age if a culvert had been replaced or reinstalled since inception. During field surveys, I recorded whether there was evidence of recent culvert replacement, such as non-vegetated or re-seeded soil, or erosion matting. These factors were considered when establishing culvert age. In cases where direct knowledge of culvert replacement or date of installation was available (i.e. observation or information from road builder), culvert dates was set accordingly.

In addition to culvert age, I quantified other characteristics of culverts that could influence the occurrence of hanging outfalls. Culvert diameter (cm) was measured on round culverts; on elliptical, oval or box culverts, the widest portion was measured. Relative culvert diameter (R_DIAM) was calculated as the ratio of culvert diameter to the bankfull width recorded for the site and reported as a proportion. Bankfull width equals the width of the active stream channel or the stream at full discharge, and is indicated by active channel marks on the bank, a distinctive change in bank slope, and transition of substrate and vegetation type (Wood-Smith and Buffington 1996). Bankfull width (+/-10 cm) was measured approximately 25 m upstream of the inlet and 25 m downstream of the outlet and reported as the average of both measurements. At multiple culvert crossings the diameter of all culverts were added and included in the calculation.

Stream Features

Stream features were derived in ArcView 3.2 using GIS data layers (hydrography, road network) and a Digital Elevation Model (DEM) obtained from the Alberta Government. The vertical spatial resolution of the DEM was +/- 3 meters; with sample points located approximately every 100 m^2.

Stream reach gradient (R_GRAD) was calculated as the % rise of the run (in meters), based on the intersection points of a 200 m diameter circle (100 m upstream and downstream from survey site) centered at the survey site and the hydrographic data layer. Rise was the difference in elevation of the intersection points, reported by the DEM. The run was the length of depicted stream reaches between points (i.e. included meanders), measured in ArcView 3.2. Reach gradient could not be calculated for sites that were missing either an upper or lower intersection point (incomplete stream layer or top end of watershed) and those sites were not included in the data set. If a lower intersection occurred below a confluence with another stream, then the lower point was set on the lower watercourse.

Statistical Estimation of Hanging Culvert Occurrence

Data summaries and analyses do not include culverts on drainage ditches, canals or non-discernable channels. The data set only includes culverts that were classified as non-barriers or hanging barriers; culverts that were classified as barriers of another type (e.g. debris) were not included.

Logistic regression was used to test if the probability of hanging culvert occurrence was influenced by three independent variables and two interactions: C_AGE, R_DIAM, R_GRAD, C_AGE*R_DIAM, and C_AGE*R_GRAD. My primary prediction was that hanging culvert occurrence would be significantly related to culvert age, with the probability of a hanging outfall increasing with time since construction (Table 2.2). I also predicted that the occurrence of hanging culverts would be higher in areas where the reach gradient was steeper because of increased scouring of streambeds below culverts, caused by high water velocities and exacerbated by extreme weather events. Similarly, I predicted that hanging culvert occurrence would be higher when relative culvert diameter was low because of increased water velocity caused by constriction of flows, again exacerbated by extreme weather events. I also considered whether there were interactions between age and the other independent variables, although the mechanisms causing such a result were less clear *a priori.*

To test these hypotheses, and develop a parsimonious model, a stepwise backward elimination process was used to remove non-significant independent variables and interactions from the model (Hosmer and Lemeshow 2000, Menard 1995). At each step in the removal, I monitored whether there were large changes (>10%) in the observed coefficients for the independent variables remaining in the model (Hosmer and Lemeshow 2000). The statistical rejection criterion for removing variables in preliminary analyses was set at $p = 0.20$ to minimize the risk of prematurely eliminating important variables (Menard 1995).

The design of this retrospective study raises concerns about spatial autocorrelation. Culvert crossings included in this study are linked by common streams and roads, potentially common road management factors, as well as landscape variables. To account for any potential spatial autocorrelation within watersheds, I used a robust cluster technique in a logistic regression modeling framework. Using watershed as the cluster, this approach uses an estimator of variance that adjusts standard errors to take into account the lack of independence between observations within a cluster (Rogers 1993). Large changes in the values of the standard errors between a naïve variance estimator and the robust model are indicative of strong correlation of observations within the cluster. With this approach, I was able to assess the importance of large-scale spatial autocorrelation as a factor influencing the occurrence of hanging culverts.

The predictive power of the final model was assessed using the area under the receiver operating characteristic (ROC) curve. Models have good predictive capability if the area under the curve is greater than 0.7 (Hosmer and Lemeshow 2000).

Statistical significance is reported at the 95 % confidence level unless noted otherwise. All analyses were performed in STATA 8.1 (Stata Corporation 2003), unless otherwise noted.

Habitat Fragmentation

I defined a watershed fragment as the portions of stream system located upstream of a hanging culvert to its headwater source (as identified in GIS). To assess how much fragmentation occurred within each of my study areas due to hanging culverts, I calculated the length of watercourses upstream of their locations. Fragmented watershed portions were described by the measure of the total of stream lengths upstream of a hanging culvert to their source, and the order of the stream on which the hanging culvert was located (i.e. root order). In many cases, hanging culverts occurred downstream of other hanging culverts, creating overlapping fragments. In such cases, the overlap was disregarded and stream lengths were measured from culvert site to source. Therefore, the number of fragments equaled the number of hanging culverts. Stream order was determined using the Strahler (1964) method.

Measurements of fragmented habitat were made in ArcView using depictions of study areas. Stream segments located upstream of hanging culvert crossings were selected manually and reach lengths and descriptive statistics were obtained using the field statistics function in ArcView data tables. The density of hanging culverts in a study area is reported per km of $< 5^{th}$ order stream, as no culvert crossings existed on streams higher than 4^{th} order in the study areas. Estimations of fragmented habitat and hanging culvert densities in the Calling and Christina areas were made by extrapolating the average proportion of hanging culverts to $< 5^{th}$ order stream crossing sites identified on map depictions but not surveyed. No variance is associated with these extrapolated estimates.

Results

Occurrence and Magnitude of Hanging Culverts

Field surveys completed in 2002 and 2003 generated data from 458 culvert crossings in the four study areas. This number includes 84 culvert crossings that were later classified as non-watercourses (cross drains, ditches or canals, non-discernable channels) that were subsequently excluded from statistical analyses. The overall proportion of hanging culverts on watercourses in all areas combined was 50% (Table

2.2). The occurrence of hanging culverts in the Swan watershed was nearly twice that of other areas. The Calling area had the lowest proportion. The large majority of hanging culverts surveyed were located on first and second order stream crossings in all areas (Figure 2.2).

The distributions of hang heights in the Notikewin, Calling and Christina areas were narrow (Figure 2.3), with the majority of outfalls being less than 50 cm high. Hang heights were more broadly distributed in the Swan River watershed, with stronger representation of >50 cm heights. Few culverts (n=11) had hang heights <5 cm.

Culvert and Stream Characteristics

Age of Culverts - Ages were assigned to 458 culverts in all study areas combined. Potential ageing error was assessed based on the range of uncertainty recorded for sites. The ageing of culverts in the Calling and Christina areas was the most precise, with only thirteen percent of sites having greater than +/- 5% potential error. Error did not exceed +/- 15% of assigned age for any site in these areas. In the Swan watershed, only 9% of sites had potential error of greater than +/- 10% and at no site did it exceed 20%. The ageing for the Notikewin watershed was the least precise, with 46% of sites having potential error of +/- 10% and 35% having between 15% and 20% error. Approximately 6% of Notikewin sites had between 80-85% error, the greatest amount found.

The age-class distribution of culvert crossings in the Swan watershed (Fig. 2.4) differed notably from the other areas, being dominated by age-40 roads. This corresponds to the rapid and extensive development of gas fields in this watershed, following exploration and discovery in the late 1950's and early 1960's. The distributions of age-classes in the Notikewin, Calling and Christina areas are similar to each other. Strong cohorts in the 22 to 26 year old (1976 to 1978) range in all three areas and an age-10 (1993) cohort in the Calling area correspond with relatively high levels of oil and gas and forestry activity during these time periods. Evidence of recent repair or replacement of culverts was observed at 2 sites in the Christina area. At one of these sites, such evidence confirmed a very young road age (built in 2002) as determined by air photo interpretation.

Relative Culvert Diameter- Relative culvert diameter was calculated for 260 sites in all study areas. Values were unavailable for 114 sites at which stream bankfull width was not available. This was generally due to ponding in the vicinity of the crossing site. The majority of culverts were less than bankfull width; the average relative culvert diameter for all areas was 0.77 (S.E = 0.029, n=260). The distributions were similar between areas (Figure 2.5). Culverts with a relative diameter as small as approximately 0.1 were recorded.

Reach Gradient- Reach gradients were derived for 345 sites on industrial roads in all study areas. Values were unavailable for 29 industrial road-crossing sites that were missing stream segments in the GIS layer. The Swan watershed had the highest average reach gradient (3.40%; S.E. = 0.17; n=122), approximately twice that of the Calling (1.64%; S.E. =0.22; n=28) and Christina areas (1.66%; S.E. =0.21; n=43). The average value in the Notikewin watershed was 2.11% (S.E = 0.13; n=152). The Calling and Christina areas contained a relatively high proportion of low gradient (<2%) sites (Figure 2.6), and the highest proportion of sites > 5% gradient was in the Swan watershed. Very low gradient (<0.2%) sites were present in all areas.

Table 2.2. Proportions of hanging culverts observed along industrial roads in study areas. Confidence intervals were calculated from the binomial distribution of the proportion.

Area	Proportion	95% C.I	N
Swan	0.74	0.65 – 0.81	122
Notikewin	0.42	0.34 – 0.48	167
Calling	0.26	0.13 – 0.43	35
Christina	0.34	0.21 – 0.49	50
All areas combined	0.50	0.45 – 0.55	374

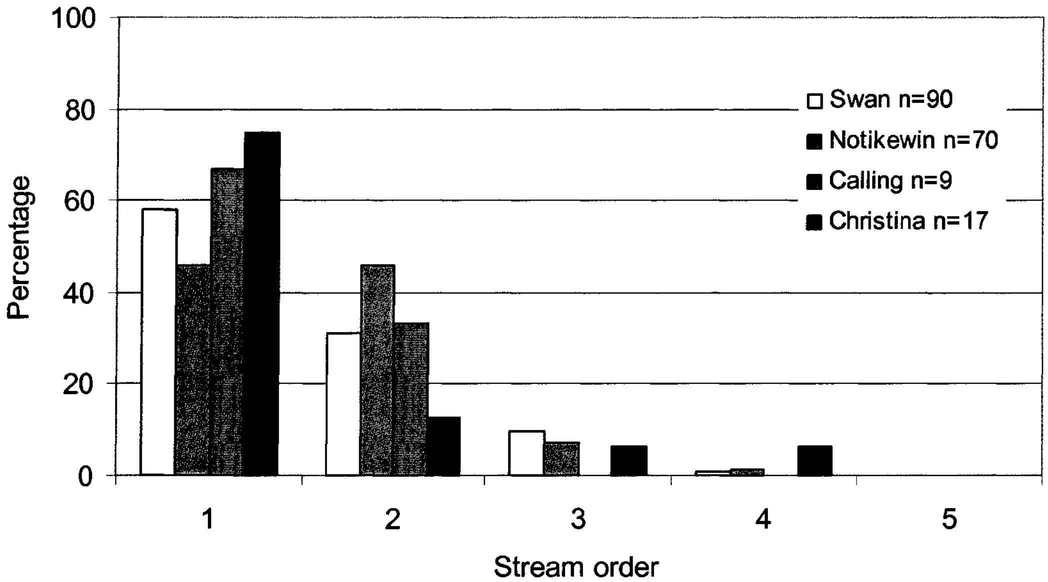

Figure 2.2. Proportions of hanging culverts on streams by order class in northern Alberta study areas, 2002-2003. *Estimated proportion of 170 first order culvert crossings, identified but not surveyed by Tchir et al. (2004).

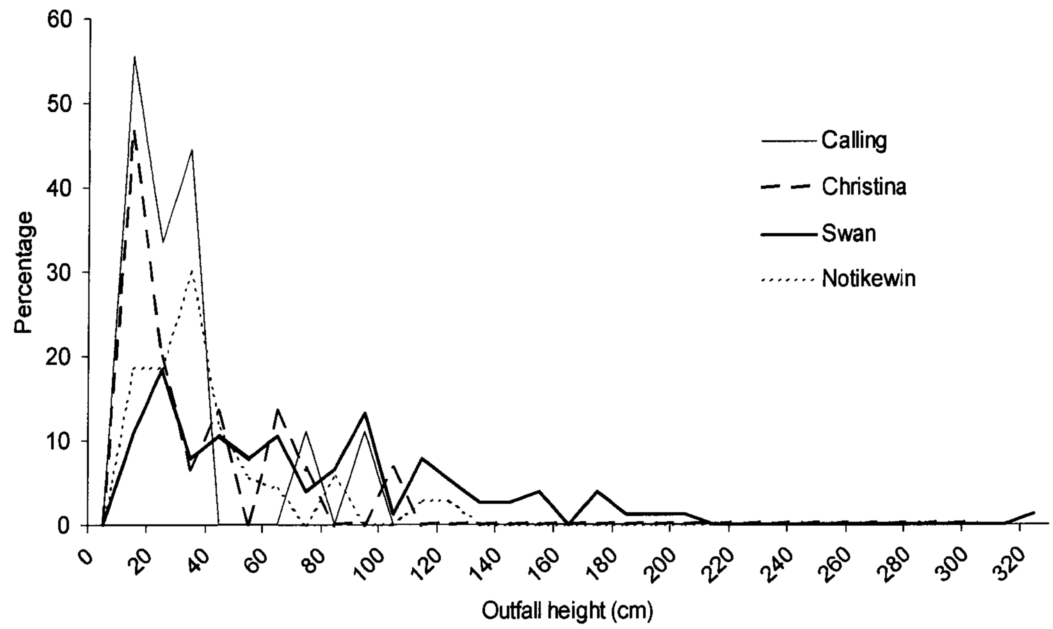

Figure 2.3. Distributions of culvert outfall hang heights in study areas in northern Alberta, 2002-2003. Hang heights are the distance between the lowest edge of the culvert at the outfall to the water surface, at time of survey.

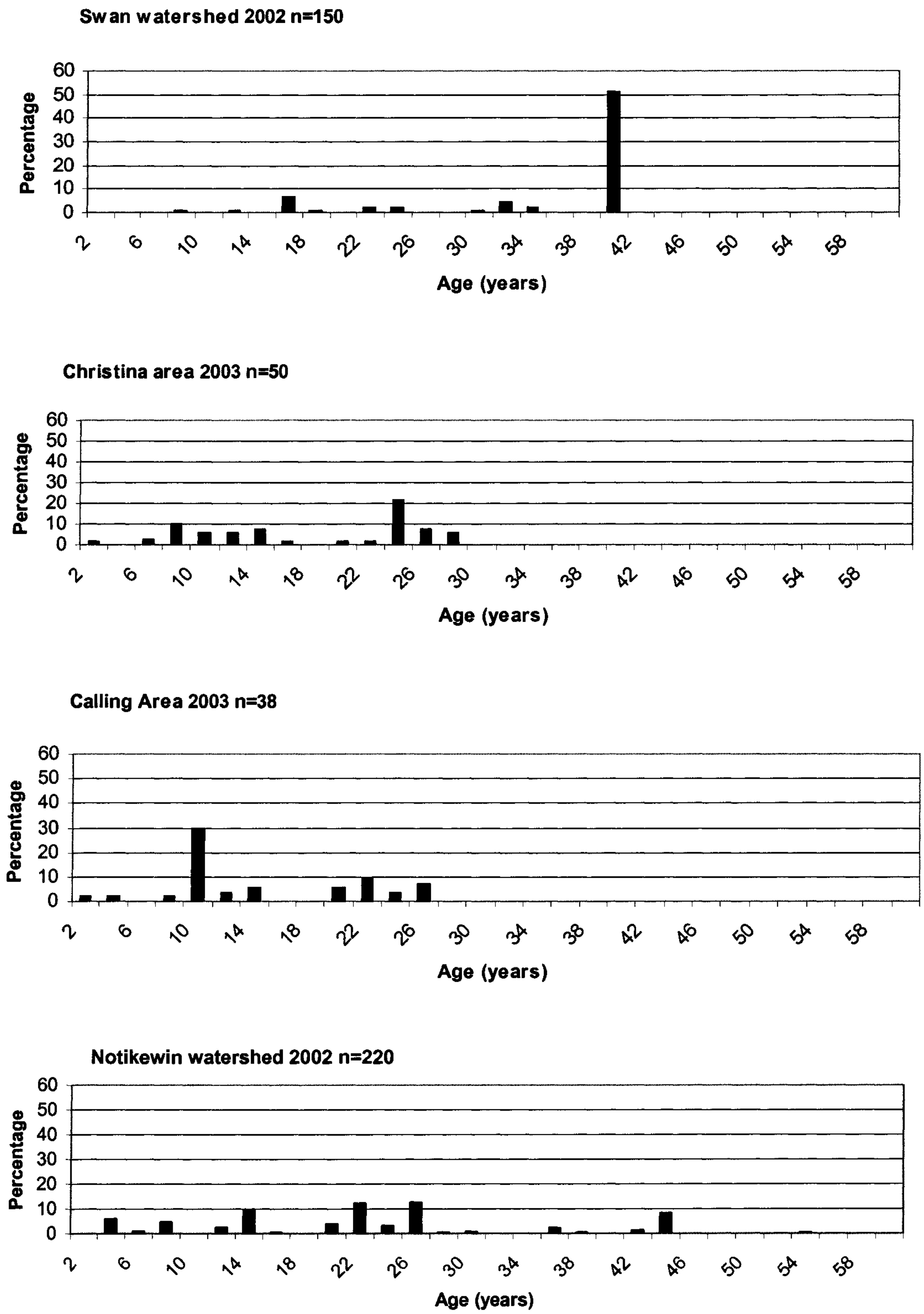

Figure 2.4. Histograms of culvert ages along industrial roads in study areas in northern Alberta, 2002-2003. Culvert ages were interpreted from road development recorded by aerial photography.

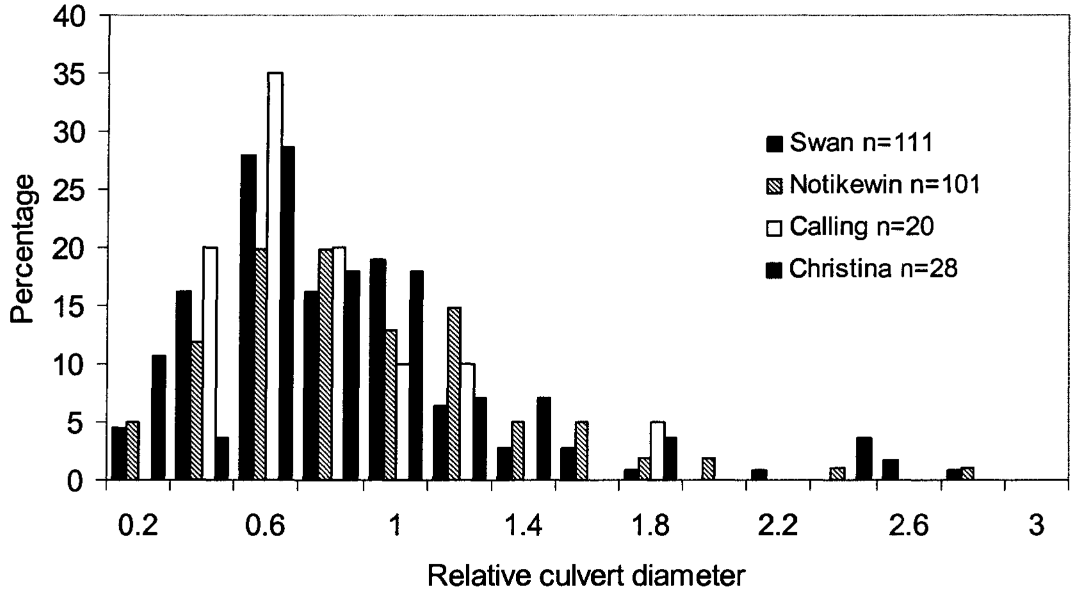

Figure 2.5. Histograms of relative culvert diameters in study areas in northern Alberta, 2002-2003. Relative culvert diameter is culvert diameter / average bankfull width of stream at crossing site. A culvert with a value of <1 constricts stream flow at > 100% volume.

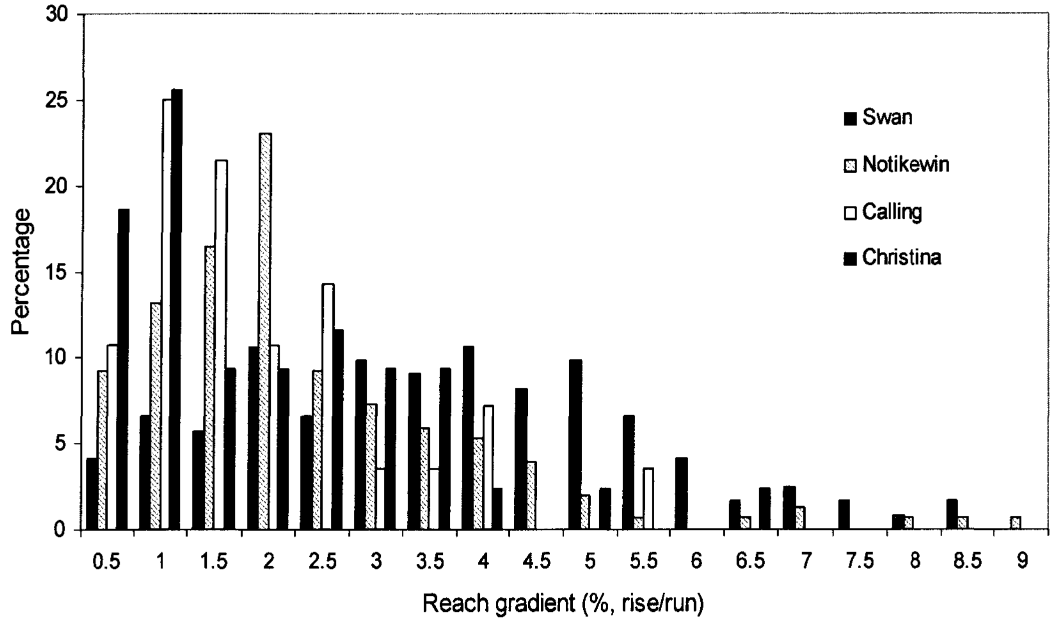

Figure 2.6. Histograms of stream reach gradients adjacent to hanging culverts in study areas in northern Alberta, 2002-2003. Gradients were derived from elevations along streams +/- 100 metres from culvert sites.

Predicting the Occurrence of Hanging Culverts

A global logistic regression model (model 1, Table 2.3) was created with the variables C_AGE, R_GRAD, R_DIAM, C_AGE*R_GRAD, and C_AGE*R_DIAM. Model fit was reasonable with a ROC value of 0.74 and pseudo r^2 of 0.11. Backwards elimination using the rejection criteria of p=0.20 resulted in the elimination of R_DIAM and R_DIAM*C_AGE.

To check for the importance of spatial autocorrelation at the watershed or area level, I then created a model using a robust cluster technique that adjusts standard errors to account for spatial autocorrelation within watersheds (model 2, Table 2.3). The standard errors for C_AGE increased 3X indicating strong spatial autocorrelation in the data. The significant interaction between C_AGE*R_GRAD also suggested spatial autocorrelation was influencing parameter estimates, as the mean R_GRAD was quite different between areas.

Given the evidence of spatial autocorrelation at the area level, I then created an unconditional fixed effects model (model 3, Table 2.3) where I included watersheds as dummy variables and the interaction between areas and C_AGE. There was strong evidence of an interaction between watershed and C_AGE. Given this interaction, I examined a series of logistic regression models for each area comparing hanging culvert occurrence vs. culvert age (model 4 series, Table 2.3). This analysis suggested that C_AGE was significantly related in the Swan and Notikewin watersheds, but not in the Calling and Christina areas, possibly a result of the relatively low sample sizes and/or a narrower age distribution in the latter groups. I also discovered that the relationship between culvert age and the occurrence of hanging culverts in the Notikewin watershed was negative. Possible reasons for this include culvert ageing error, or inability to identify and account for replacement of old hanging culverts with new structures that are not hanging or young culverts not originally installed to pass fish. Accepting the ageing results for the Notikewin watershed as accurate left me to consider that either culvert replacement or a relatively high proportion of poorly installed young culverts were causes, alone or in combination. Although culvert maintenance and poor installation are undetectable and unaccounted for in all areas, the seemingly large effect of these factors in the Notikewin watershed confounds the ability of a model that includes this area to project to a broader spatial extent. Based on this assessment, the Notikewin watershed data were eliminated from subsequent models.

A fifth model (Table 2.3) of hanging culvert occurrence vs. age and reach gradient for all areas excluding the Notikewin watershed produced a positive age-relationship with good fit. The pseudo-r^2 value for this model was 0.22 and the area under the ROC curve was 0.81. Area as a dummy variable and the interaction between watershed & C_AGE were dropped from the model when the Notikewin data was removed. To check again for spatial autocorrelation, the model with the Notikewin data removed was run using the robust cluster. There was virtually no change in the SE for this model relative to a standard logistic regression model. This indicated that generating pooled parameter estimates for C_AGE and R_GRAD was reasonable for all areas except the Notikewin.

The occurrence of hanging culverts increased significantly with age and reach gradient, with the proportion of hanging culverts in a cohort increasing as gradient increased. In a low gradient (~1%) situation the modeled proportion of age 20 culverts that were hanging was 0.3 (Figure 2.7). In a moderately high gradient (~3%) location, the proportion increased to 0.5. The probability of hanging outfall occurrence in < 5-year-old culverts ranges was under 0.2 in low gradient areas and between 0.3 – 0.4 in high gradient areas.

Habitat Fragmentation

The estimated density (n/ stream km) of hanging culverts, and proportion of small stream habitat fragmented was greatest in the Swan watershed (Table 2.4), being at least 4 times greater than other study areas. In each area, the size of fragments (km of stream reaches upstream of hanging culverts) created by a hanging culvert generally increased as stream order at the culvert site (root order) increased (Figure 2.8). For all areas combined, fragment size increased exponentially with root order class (Figure 2.9). However, there was considerable variance in the size of order 4 fragments, a result of their low number (n=3). The sizes of these three 4^{th} order fragments were 25, 31 and 85 kilometers of watercourse. This latter fragment was the largest measured, and occurred in the Christina area.

Table 2.3. Parameters from different logistic regression models evaluating the relationship of factors on occurrence of hanging culverts. Odds ratios are followed in parentheses by standard error. Names appearing in brackets are names of northern Alberta study areas (2002-2003). Using model 5 as an example, the odds ratio can be interpreted as: for each 1 year increase in the age of a culvert there is 1.065 times greater chance that the culvert will hang.

Model	Variables Included	Odds Ratio (OR)	95% C.I. for OR	P	N
1	C_AGE	0.971 (0.016)	(0.939 – 1.003)	0.08	345
	R_GRAD	0.869 (0.128)	(0.652 – 1.159)	0.34	
	C_AGE*R_GRAD	1.022 (0.006)	(1.010 – 1.035)	<0.001	
2	C_AGE	0.971 (0.043)	(0.889 – 1.060)	0.51	345
	R_GRAD	0.869 (0.180)	(0.579 – 1.304)	0.50	
	C_AGE*R_GRAD (Autocorrelation corrected)	1.022 (0.007)	(1.008 – 1.037)	0.002	
3	C_AGE	0.978 (0.068)	(0.853 – 1.121)	0.75	345
	R_GRAD	0.834 (0.128)	(0.618 – 1.127)	0.24	
	C_AGE*R_GRAD	1.020 (0.007)	(1.007 – 1.0330)	0.002	
	WATERSHED	.	.	0.10	
	WATERSHED*C_AGE	.	.	0.03	
4	C_AGE (Notikewin)	.968 (.014)	.942 - .996	0.023	167
	C_AGE (Swan)	1.047 (.022)	1.005 - 1.092	0.029	122
	C_AGE (Calling)	1.013 (.056)	.908 - 1.130	0.816	33
	C_AGE (Christina)	1.004 (.0395)	.930 - 1.0845	0.918	50
5	C_AGE	1.065 (.0155)	1.035 - 1.096	0.000	192
	R_GRAD (excluding Notikewin)	1.596 (.172)	1.292 - 1.9725	0.000	

z : = 1/(1 + exp (-(-2.607785+ (.4676919*y) + (.0628866*x))))

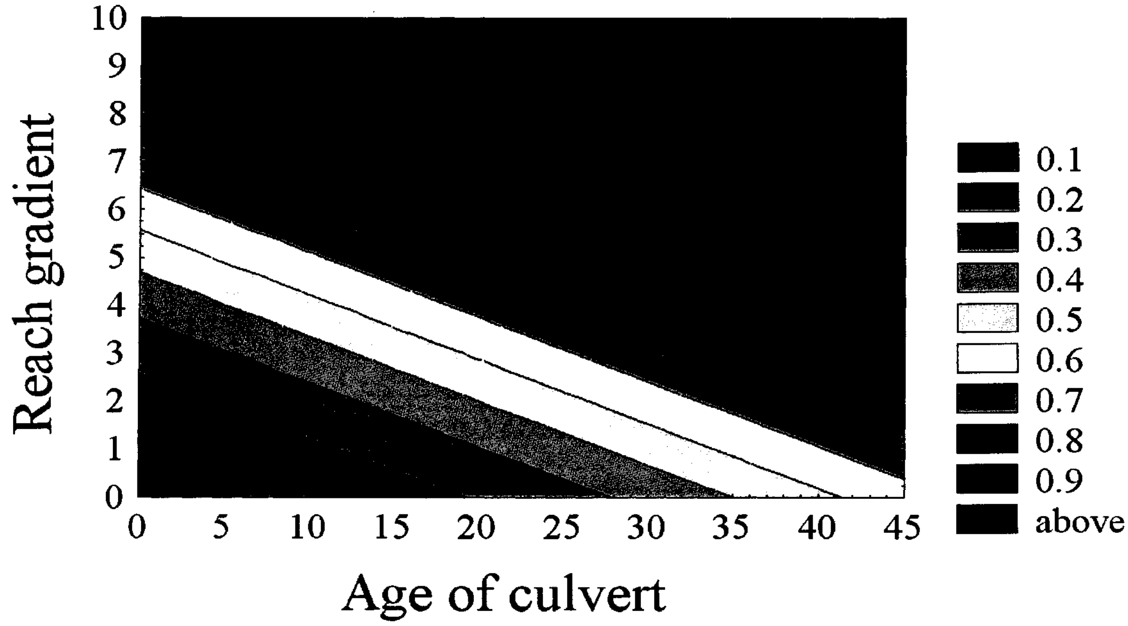

Figure 2.7. Zone plot of predicted probability of hanging culvert occurrence based on logistic regression model output (model 5). Slope equation is shown at top of figure. The predicted probability of hanging culvert occurrence is z, y is reach gradient and x is culvert age.

Table 2.4. Descriptive statistics of lotic fragmentation attributes caused by hanging culverts along industrial roads in study areas in northern Alberta, 2002-2003. Watershed fragments are stream reaches upstream of hanging culvert to source, as depicted by spatial data. *Swan watershed data do not include first order watercourses.

Area	Number of watershed fragments	Estimated proportion of < 5th order streams fragmented (km)	Estimated hanging culvert density (n / stream km)
Swan*	90	19.9% (329/1653)	0.063
Notikewin	70	5.4% (453/8389)	0.011
Calling	9	4.8% (50.4/1050)	0.012
Christina	17	4.5% (238/5289)	0.005

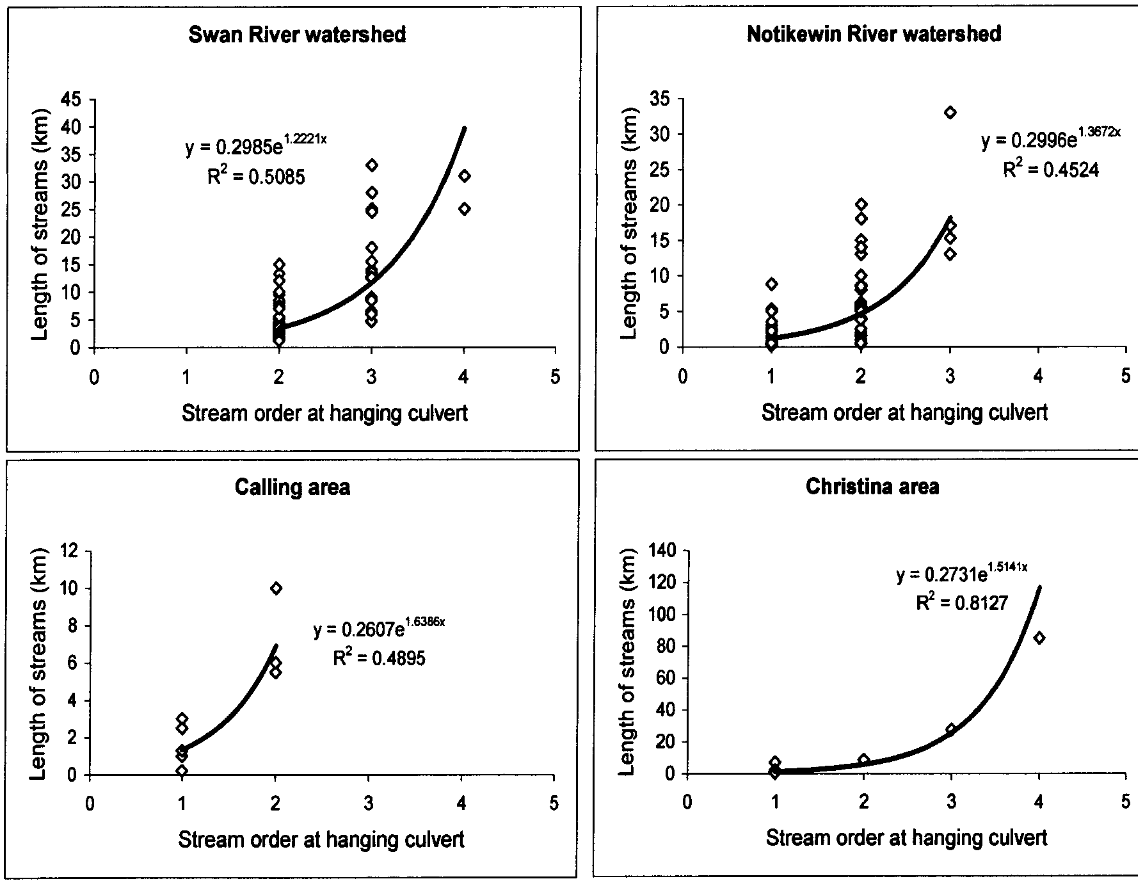

Figure 2.8. Size and root order class of watershed fragments caused by hanging culverts in northern Alberta study areas, 2002-2003. Root order class is the stream order at the hanging culvert location. Models are fitted with an exponential curve.

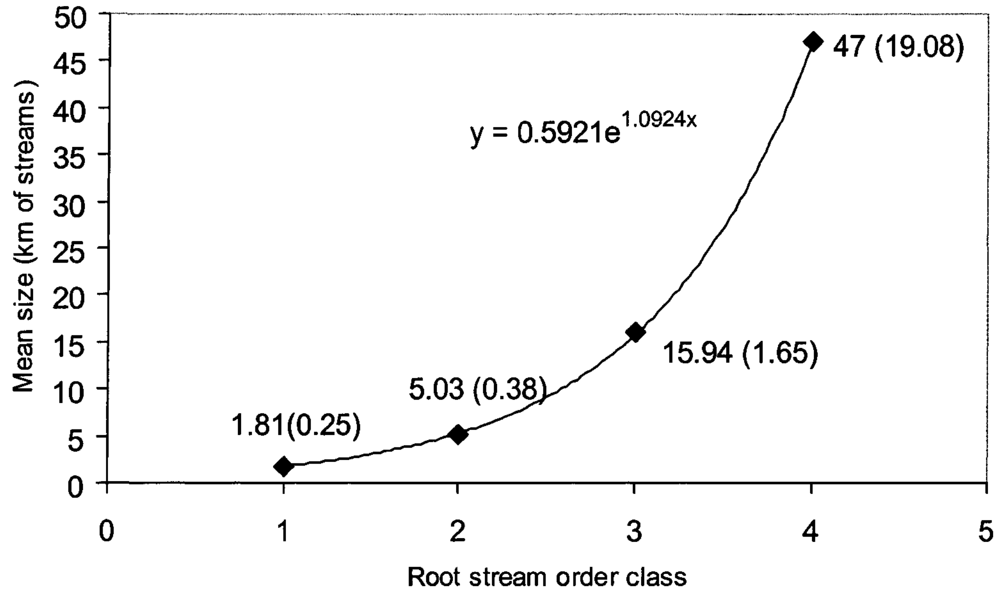

Figure 2.9. Average size of watershed fragments (stream reaches upstream of hanging culverts) caused by hanging culverts in northern Alberta, 2002-2003, by root stream order class of hanging culvert – all study areas combined. Mean values are shown with standard error in parentheses. Note: the sample size of order 4 class fragments was n=3; for order 1, 2, and 3 class fragments, n=51, 101, and 26, respectively.

Discussion

Hanging culverts are common along ageing industrial roads in northern Alberta. While the results suggest that many culverts have become hanging over time, it is possible that fish passage consideration was either not considered or not required for some culvert crossings on some of these streams during the initial construction phase. Tchir et al. (2004) argued that considerations of fish passage likely became more influential in culvert design in Alberta during the early 1990's, coinciding with the rapid expansion of the forestry industry. Most of the culvert crossings surveyed in this study pre-date that time.

In a retrospective study such as this, between-area comparisons of hanging culvert occurrence need to consider stream flow dynamics and hang height. The flows of streams in the Swan and Notikewin watersheds were below average during the surveys, and it is reasonable to assume that some hanging culverts in these areas with low hang height may not be hanging during higher flows. Conversely, stream flows in the Calling and Christina watersheds were at or above average during the survey period, and the occurrence of hanging culverts in these areas could be higher in drier periods. Under these conditions, the difference between areas would be smaller, the actual degree of which would be partially dependent on the distributions of hang heights. The Swan watershed had a relatively low proportion of culverts with hang heights < 20 cm, whereas the Calling and Christina areas had a relatively large proportion. Given the extreme hang heights, an increase in stream flows in the Swan watershed may result in the reduction of only a small proportion of hanging culverts relative to the other areas.

As predicted, I found a significant positive relationship between culvert age and reach gradient and the occurrence of hanging culverts. However, this relationship was not completely consistent across all of my study regions. The factors creating a negative age-relationship for hanging culvert occurrence in the Notikewin watershed are not clear. I believe this relationship is most likely indicative of unaccounted culvert maintenance, mediating the development of hanging culverts over time. It may also indicate recent installation of culverts without consideration of fish passage (i.e. very young hanging culverts). The decision to remove the Notikewin watershed data from latter logistic regression models was justified on the basis that such factors cannot be quantified or accounted for and may not be reflective of conditions at a larger spatial extent.

Due to the retrospective nature of this study, I could not determine precisely when in the past a hanging culvert developed, only that it had occurred. Therefore, the hanging culvert occurrence rates indicated by my analyses have to be considered underestimates, the degree of which is not easily quantified. True annual occurrence rates could be higher.

Ages assigned to roads using aerial photo interpretation showed good precision and accuracy relative to known patterns of industrial and agricultural development in focal areas and is not a likely explanation for the Notikewin discrepancy. However, true culvert age could differ from assigned age if culverts were replaced. Direct evidence of recent culvert replacement or reinstallation was only obtained by field surveys, and such observations were rare. Obtaining accurate administrative information regarding culvert installation or replacement was not feasible, as it was not well archived or readily accessible. The use of non-removable date markings on culverts, indicating year of installation would resolve future uncertainty. Further, the development and use of a common electronic data management system to monitor culvert installation and maintenance by road builders and governments would facilitate effective culvert management.

Observations of young culverts with hanging outfalls may also indicate an element of flow-related stochasticity inherent in the process of their development. High stream flow events can occur at any time, with the potential to cause a hanging culvert outfall via acute scouring of the streambed at the outfall. In fact, it may be best to view culvert age (i.e. time) as a surrogate variable for the occurrence of high flow events. In other words, time alone does not cause culverts to hang, but rather the effects of water flowing over time cause them. Predictive capability of models of hanging culvert occurrence may be improved by the inclusion of stream flow pattern over time, particularly focused on periodicity of high flow events.

Young hanging culverts may also be indicative of improper installation, or installation without consideration of fish passage. Gibson et al. (2005) assessed the status of culvert crossings constructed during 1999-2002 across streams containing trout and salmon along a primary highway in Labrador. They found that approximately 17% of these young culverts were hanging, and concluded that they were improperly installed, providing strong evidence that improper installation can occur even in prominent situations, affecting highly-valued sport fish. The possibility of hanging culverts developing stochastically underscores the need for regular monitoring of all culvert crossings, particularly those in high gradient areas. The possibility of improper installation highlights the need for increased compliance and enforcement of aquatic habitat protection regulations.

The lack of a significant relationship between culvert diameter and occurrence of hanging culverts in this study may be a reflection of the fact that the large majority (approximately 80%) of culverts associated with industrial roads in study areas were smaller than bankfull width. Such culverts must constrict stream flow to varying degrees and frequency. As relative culvert diameter decreases below bankfull width, any additional effect of further size reduction may not have been discernable. Conversely, the relatively low proportion (27%, 70/260) of culverts with diameter equal or greater than bankfull width may have been insufficient to detect the effect of such culvert sizing on reducing hanging culvert occurrence.

I attempted to include upper contributing watershed area, defined as the area that contributes surface flow to a designated location, in the suite of predictor variables. Presumably the larger upper watershed area could increase the number and degree of high stream flow events. The variance in the current provincial Digital Elevation Model (+/- 3 m vertical error) was too great to consistently provide data of sufficient quality required in the analyses. In low gradient areas, the vertical error represented a large horizontal error. Watershed areas, particularly larger ones, were grossly misrepresented relative to intrinsic stream lengths, resulting in bias. Sufficient accuracy in a DEM is necessary to provide data of sufficient quality to support such analysis.

The final logistic regression model was not validated. Because of concerns regarding sample size and variance, all available survey sites were included in the analyses. The most definitive validation would be to conduct culvert assessment and age determination in a new study area, comparing predicted results against observations. The objectives of future assessments of culverts in boreal watersheds should include validation of my model wherever possible. To facilitate validation, observational studies of culverts of known age are recommended.

Guidelines regarding fish passage constraints at the site and jurisdictional levels are commonly focused on large-bodied sport fishes (Moore et al. 1999, Government of Alberta 2002). Such a focus may not prevent culvert fish barriers from having serious fragmentation effects on small-bodied fishes, such as cyprinids, that are less powerful swimmers and jumpers. Schmetterling and Adams (2004) documented fish movement in a small Montana stream. They found that both resident trout and sculpins displayed considerable bi-directional (upstream and downstream) movement during summer months, underscoring the need for habitat connectivity for both small and large fishes. They recommended that fish passage criteria for man-made structures be focused not on the swimming performance of adult salmonines, but on juvenile life stages or co-resident species having poor swimming ability. A liberal criterion for defining a hanging culvert (> 1cm hang height) was used in this study to increase the scope of relevance to small-bodied fishes. However, even with such a liberal definition only a few (n=11) culverts with very low hang heights were detected. With this approach, subsequent modeling of landscape level consequences of the fragmentation effects of hanging culverts could be more broadly related to all life stages of all fish and perhaps to other aquatic species occurring in study areas.

Equally important however, is recognizing that this study relates to hanging culverts only. Other culvert-related movement barriers, such as those caused by debris blockages and excessive water velocity will increase the actual fragmentation effects on habitats and fishes. While such barriers are assumed to be relatively ephemeral compared to hanging culverts, their overall effects on fragmentation are unclear. Studies that describe differences between communities and populations of fishes above and below suspected movement impediments may provide the most definitive evaluation of fragmentation effects. The assessment of culvert-related watershed fragmentation caused by hanging culverts alone should be considered a conservative approach.

In this chapter, my assessment of fragmentation was based on measurement and description of physical features alone. The biological effects of fragmentation are related to fragment size, as per the species-area relationship, which describes the size-related capability of habitats to support populations of organisms (Matter et al. 2002). A common understanding in conservation biology is that small populations have a higher risk of extinction than larger populations due to demographic, genetic and environmental stochasticity (Shaffer 1981, Lande 1988). Morita and Yamamoto (2002) demonstrated that this is valid for lotic populations of white-spotted charr (*Salvelinus leucomaenis*) isolated by dams in Japan. In the boreal landscape, environmental dynamics may be a powerful factor regulating populations, exacerbating the species-area relationship. From the perspective of fish, natural events such as winter and drought are population-limiting processes, particularly if they occur in extreme severity or in combination. The effects of such events increase as stream size decreases, making small streams unstable and relatively unfavorable habitats for fish. Merkowsky (1998) observed that boreal fish species diversity declined with stream order, and it is reasonable to suggest that this is indicative of a general inverse relationship between declining stream order and increasing risk of species extirpation. The assessment of biological effects of fragmentation at large spatial scales may be facilitated by the development of a stream order-based risk of extirpation over time.

Currently, no thresholds exist regarding habitat fragmentation or loss in watercourses in Alberta. The business-as-usual approach by regulatory agencies is that of "no net-loss" of fish habitat (DFO 1986, Harper and Quigley 2000, 2005), based on the principles of avoiding loss or commensurate compensation for loss, and makes no accommodation for tolerable loss or degradation of habitat. The reference to fish in federal legislation includes non-sport fishes at every life stage. Technically, this legislation makes the development of thresholds impractical, as doing so would require establishing tolerable fragmentation. The fact that fish passage criteria relative to existing culvert road crossings in Alberta are based on adult sport fish and only make allowance for high flow-related delays in fish movements for spawning periods further widens the gap between legislation and practical application. The traditional approach by industrial road builders for culvert design, based on predicted stream flow regimes from theoretical hydrologic models and adult sport fish swimming performance, is perhaps a consequence of confounding law. The lack of thresholds impairs the development of road crossing management strategies aimed at maintaining ecosystem integrity.

The results of this study provide information that can be used to select high-risk watersheds on which to focus culvert monitoring and remediation efforts and to plan future road development. Removing or replacing hanging culverts on high order stream crossings has high relative benefit in terms of the size of watershed fragment reconnected; however, this may need to be balanced against risk of extirpation within fragments. High gradient areas with old roads should receive highest priority for culvert monitoring and remediation of hanging culverts. Based on the probabilities presented in Figure 2.7 and an arbitrary threshold of hanging culvert occurrence of 30%, the expected culvert replacement interval in high gradient (3-4%) reaches is approximately half as long as that in low gradient (1-2%) areas. Assuming that culvert maintenance (i.e., replacement or reinstallation) matches pace with the development of hanging outfalls, the costs of maintaining a hanging culvert-free road network in high gradient areas could be double that for flatter locations. Analyses of cost-effectiveness of culverts versus alternative crossing structures (e.g., bridges) may indicate that the long-term costs of maintaining culvert crossings are not lower.

Conclusions

The traditional management approach of road builders and regulatory agencies has failed to prevent the development of hanging culverts and fragmentation of small boreal streams in Alberta. The use of culverts even in the most favorable conditions is associated with a risk of hanging outfall occurrence and consequential habitat fragmentation, threats to species persistence, and potential violation of existing regulations. This risk escalates with time, at a rate that increases with increasing stream gradient. The present number of hanging culverts in northern Alberta represents a large and increasing accumulated management issue.

Models designed to forecast or evaluate the landscape-level fragmentation effects of road development incorporating culvert stream crossings should include culvert ages and stream reach gradients as parameters affecting hanging culvert occurrence. The proportion of culvert crossings by stream order, and the size of habitat fragment associated with order class can be used to quantify watershed fragmentation. The biological effects of hanging culverts in lotic systems are well linked conceptually to this metric; however, assessment of effects may also consider the risk of extirpation associated with the order classification of fragments.

Chapter 3 – A simulation model-based assessment of alternative strategies for reducing lotic fragmentation caused by hanging culverts along industrial roads in Alberta's boreal forest

Introduction

Despite the recognition of the negative ecological consequences of fragmentation on fish populations, current road and culvert management practices are failing to prevent the occurrence of hanging culverts at road crossings of small streams in Alberta's boreal forest and elsewhere (Tchir et al. 2004; Gibson et al. 2005; also see previous chapter). Current business-as-usual (BAU) practices used by industrial road builders and regulatory agencies when making decisions on the type and design of stream crossing deemed acceptable typically involve assessments of stream flow regimes derived from theoretical models of average stream characteristics, local hydrology, swimming performance of adult sport fishes, and timing of spawning migrations (DFO 1986; Government of Alberta 2002). BAU practices also use short-term cost-benefit analyses when deciding whether to use a culvert or alternative crossing structure at streams. In theory, these approaches are intended to minimize costs while preventing stream fragmentation and negative impacts on aquatic species. However, these models fail to consider long-term costs of future replacement, potential fines imposed by regulatory agencies (e.g., Fisheries Act convictions resulting from fish habitat damage or loss), and the larger scale cumulative effects of multiple culvert failures. The consequence of current BAU practices is the proliferation of hanging culverts in boreal watersheds and fragmentation of streams at increasingly larger spatial scales with concomitant impacts on fish communities and perhaps aquatic biodiversity in a broader sense.

Extensive road construction has occurred in Alberta's boreal forest as a result of forestry and petrochemical industrial activities. Overall, the current average road density is approximately 0.25 km/km^2 (Stelfox, pers. comm.). However, in highly developed locations, road densities as high as 6 km/km^2 exist, arguably a practical maximum density. The rate of road development is expected to increase over the next 50 years (Schneider et al. 2003) with some estimating that within 100 years, the overall density of roads in northern Alberta will reach 1 km/km^2 (Stelfox, pers. comm.). Clearly, better road and culvert management practices need to be developed and implemented to minimize stream fragmentation.

This chapter builds on my observational study of hanging culverts in the boreal forest of northern Alberta. In Chapter 2, I quantified the occurrence of hanging culverts along industrial roads in four focal watersheds and determined the influence of culvert and landscape factors on hanging culvert development. Current levels of road development and habitat fragmentation were also assessed. Here, I quantify spatial relationships between streams, roads, and stream crossings using empirical and simulated spatial data, and incorporate the empirical information from Chapter 2 into a simulation model that forecasts stream fragmentation. I then use the model to conduct scenario analyses, comparing alternate road management strategies and their potential effects on stream fragmentation, relative to financial costs. The purpose of this study is to develop a modeling tool to quantify future watershed fragmentation arising from hanging culverts and to discover cost-effective management actions to reduce culvert-caused fragmentation of boreal watersheds.

Methods

Overview

The construction of this model had three components. First, I conducted map-based simulations using depictions of spatial data from the study areas described in the previous chapter to quantify relationships required as modeling functions (i.e. the proportion of habitat fragmented by hanging culverts at varying road and stream densities). Second, I combined these relationships with the previously described culvert failure relationships into a simulation model to describe future conditions in contrasting low and high gradient simulated watersheds, and assess the relative influence of road management variables (i.e. management "levers") on degree of stream fragmentation therein. Lastly, I used the model to conduct scenario analyses of alternate road management strategies to determine potential best management practices for road development in a previously undeveloped area relative to managing a landscape already dissected with high road density, and with substantial numbers of culverts. Specifically, I addressed the most cost-effective ways of allowing road development in a watershed while minimizing fragmentation risk. I also searched for cost-effective ways of remediating existing conditions in already fragmented landscapes of low and high landscape gradient. Finally, I compared the cost-effectiveness of bridges as an alternative to culverts.

Model Design

I developed HANGFRAG, a dynamic, process-based simulation model in STELLA® language (ISEE Systems 2001). The basic components of this non-spatial model are road and stream densities, time (culvert age) and slope of land (Figure 3.1). User-defined road and stream densities interact to result in predicted densities of stream crossings, a large proportion of which are classified as culvert crossings (culverts exist on < order 5 stream crossings). Culverts develop hanging outfalls over time; at a rate related to land slope (see previous chapter). Hanging culverts function as one-way biological flow regulators, impeding upstream movement of organisms and fragmenting upstream reaches. The amount of fragmented habitat is positively related to stream order at the crossing site (i.e., the higher the order, the greater the proportion of fragmented habitat, see previous chapter). The primary output of the HANGFRAG model is the proportion of contiguous small stream (< order 5) habitat in a simulated watershed at different time intervals and is defined as the % length (km) of unfragmented stream reaches, occurring downstream of all hanging culverts. The user may also simulate the effects of management practices such as removing hanging culverts or replacing them with non-hanging culverts or bridges. Other management practices that may be simulated are poor installation (i.e. immediate failure) of varying proportions of culverts, changes in road density, and avoidance of stream crossings. Management practices are linked to economic costs of road-related infrastructure. The HANGFRAG model also has road density and infrastructure cost as outputs, as well as an accounting of culverts installed and replaced. The model is run in annual time-steps, with simulations conducted over a period of 100 years.

Model Parameters

HANGFRAG parameters and functions were developed to represent the process of stream fragmentation arising from industrial road development in two simulated landscapes that represented the ends of the spectrum of topographic conditions and levels of initial road development (pristine and developed) that are likely to occur in Alberta's boreal forest (as observed in field studies; see Chapter 2): Watershed HILLS, comprised of high gradient streams, and Watershed PLAINS, comprised of low gradient streams.

The spatial extent of all simulations was 100 km^2 (approximately one township), therefore the topographic parameters reflect those expected on average for this areal extent. The parameter sets of my starting landscapes were derived from direct measurements or estimates from field studies, spatial data analyses and expert opinion (Table 3.1). All spatial data analyses were conducted using ArcView 3.2 (ESRI 2000).

Alternate management scenarios differed in the level of initial road impact at simulation start, specifically, the initial density of roads. Road development in pristine, near roadless areas was represented by low initial impact. The road density in these scenarios was set to emulate the initial road development step in a pristine watershed, that is, the construction of a single trunk road across the area. Watershed remediation of developed areas already dissected by roads was represented by high initial impact or high initial road density. The initial hanging culvert proportion in low initial impact scenarios was held at the same level as other scenarios, to ensure comparisons were based on the focal manipulated variables (i.e. culvert replacement). Also, I had no quantified basis on which to change this setting.

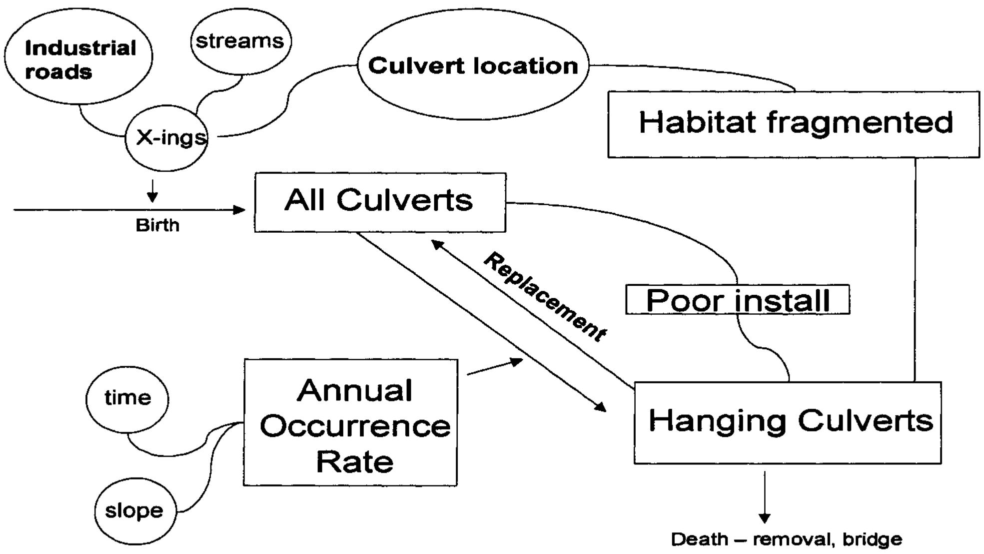

Figure 3.1. Diagrammatic representation of HANGFRAG culvert fragmentation model. Written in STELLA® language.

The total invested financial value (Canadian dollars) of access infrastructure of forecasts and model runs was measured and reported as the sum of the costs of roads built ($25,000/ km) and culverts installed ($5,000/culvert) and replaced ($12,500/culvert) over the entire course of the simulation period. The infrastructure cost of bridges-only scenarios was the sum of the costs of roads built and all crossings installed at the rate of $40,000/bridge. Averaged cost rates were determined by expert opinion (Crawford, pers. comm.). The value of roads and culverts existing at the start of simulations was included in the sums. Cost analyses did not include asset depreciation, net present value or alternate uses of funds not spent in less costly strategies. Infrastructure costs are reported without variance.

Model Functions

Habitat fragmentation function –A primary function in HANGFRAG was the proportion of fragmented small stream habitat in a simulated watershed related to the abundance of hanging culverts. In order to support model forecasting, this relationship was derived from a series of GIS-based simulations with hanging culvert densities greater than those observed in the empirical studies described in chapter 2. In these simulations, road (including proposed roads appearing as undeveloped Licenses of Occupation) and hydrography layers in 100 km^2 sample areas containing between 100-200 km of watercourses were depicted. Each intersection of road and stream was designated as a hanging culvert crossing. Hanging culverts were randomly removed (i.e. assigned non-hanging status) until a desired hanging culvert density was depicted. All stream reaches upstream of hanging culverts were then measured, summed, and the proportions of fragmented to unfragmented stream lengths in the sample areas were calculated. This process was repeated in different sample areas in high and low gradient watersheds to capture natural variation of stream networks, and for a range of densities of hanging culverts that may reasonably be expected to occur in Alberta. The relationship between hanging culvert density and proportion of stream fragmentation (Figure 3.2) was fitted to a logarithmic curve to account for the potential for hanging culverts at low density to cause a disproportionately high amount of fragmented habitat if they are located on a high order stream. In the HANGFRAG model, this function was represented as,

$$F = 0.175\ (\text{logn}\ (C_d)) + 0.841,$$

where F is the proportion of stream habitat fragmented, and C_d is the density of hanging culverts.

Road location function–The density of stream crossings was calculated as a function of densities of roads and small (< order 5) streams using a series of GIS-based simulations. Simulations were done by first overlaying a 100 km grid of roads (i.e., 5x5 grid of 10 km roads) in 100 km^2 sample areas. Each intersection between road and small streams was classified as a stream crossing, and the number of crossings (n) in a sample area was recorded as crossing density (i.e., n / watershed km^2). The product of road density and stream density was strongly correlated to culvert density (n / 100 km^2) (Figure 3.3). In HANGFRAG this function was represented as,

$$C_d = R_d \times S_d \times R_l,$$

where C_d is the density of culverts, R_d is road density, S_d is stream density and R_l is the slope coefficient of the regression line, describing the ratio at which culvert density increases with increasing road and stream density (y=0.509x; see Figure 3.3). Road builders may align roads without consideration of watercourses (as simulated by a grid pattern), avoid crossing streams, or preferentially cross them. This may depend on topographic constraints or be reflective of best management practices. In this model, a function was included that represented varying propensity to cross streams to serve as a road management variable. In the model, decreasing or increasing the slope coefficient of the culvert density relationship simulated road builders' avoidance of, or attraction to stream crossings, respectively.

Hanging culvert occurrence function– The occurrence rate of hanging culverts is related to adjacent land slope and age of the crossing (see previous chapter). In HANGFRAG, gradient is user-defined and age-related failure rate is a key function. To derive this function, I determined the slope coefficients for linear regressions of age vs. proportion of hanging culverts for 3 landscape gradient classes (i.e., <2%, 2-4%, and >4%). Each slope coefficient was the annual hanging culvert occurrence rate for each gradient class. These rates were compared to the average gradient of sites in the above categories to derive a relationship between annual hanging culvert occurrence rate and gradient (Figure 3.4). User manipulation of average reach slope therefore changed the value of the x-coefficient in the functional equation in the HANGFRAG model.

I chose this approach for three reasons. First, despite a lack of significant difference between gradient and hanging culvert occurrence rate (the variances around estimates overlap), the trend was generally towards a positive relationship. It seemed reasonable to believe that steeper landscapes are associated with higher rates of hanging culvert occurrence. I chose to model on this basis, to avoid committing a Type II error, by concluding no relationship exists when in fact it does. Secondly, this approach lent itself well to showing variance and incorporating uncertainty in this component of the model. Third, because of a lack of true 0 to 5 year old culverts, the logistic regression model had to extrapolate backwards. As a consequence, the instantaneous hanging outfall occurrence rates for these cohorts appeared to be excessively high. Linear regression provided more conservative rates that were intuitively more appropriate.

Table 3.1. Parameter set of HANGFRAG culvert fragmentation model, showing settings of business-as-usual forecasts for simulated watersheds HILLS (high gradient) and PLAINS (low gradient).

Parameters	Units	Watershed HILLS BAU forecast	Watershed PLAINS BAU Forecast
Initial industrial road density [a]	km / km^2	0.5	0.2
Stream density (< order 5 streams) [a]	km / km^2	1.5	1.0
Average watershed reach gradient [b]	% rise / run	3.4	2.1
Initial culvert density [c]	n / km^2	0.1	0.05
Initial hanging culvert proportion [c]		0.7	0.35
Annual road build rate [d]	%	2	2
Road location [e]		0.5	0.5
Annual culvert replacement rate	n / year	0	0

[a] Based on average of measurements of features in sample blocks within focal watersheds from Chapter 2 (Swan and Notikewin rivers). Calculated in ArcView.
[b] Values calculated for Swan and Notikewin river watersheds. See Chapter 2.
[c] Values observed in surveys of Swan and Notikewin river watersheds. From Tchir et al. (2004).
[d] Forecast value of 2% is based on review of corporate and government business plans, done by Stelfox (pers. comm.). Schneider (2002) suggested that road development could be reduced to as low as 1% annually through collaborative planning.
[e] An index of the relative propensity of roads to cross streams (see text for definition). A value of 0.5 corresponds to random road location; the lower the value, the greater the avoidance of crossing streams.

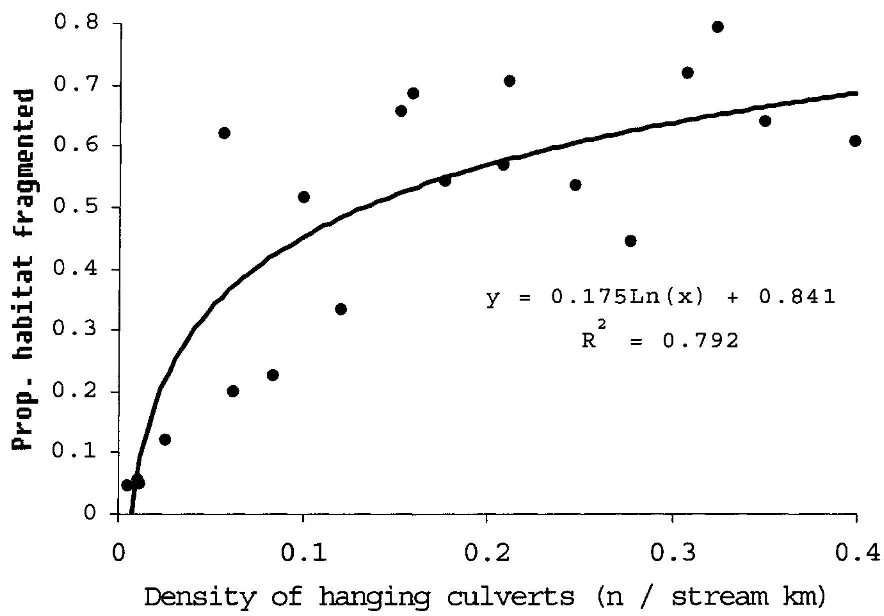

Figure 3.2. Relationship between hanging culvert density and the proportion of small stream (< 5^{th} order) habitat fragmented in a watershed. Derived from GIS-based (ArcView) simulations of watershed fragmentation resulting from hanging culverts. The proportion of watershed fragmented is based on the length of small stream reaches located above hanging culverts, relative to the total length of such streams in 100 km^2 sample blocks from Alberta study areas.

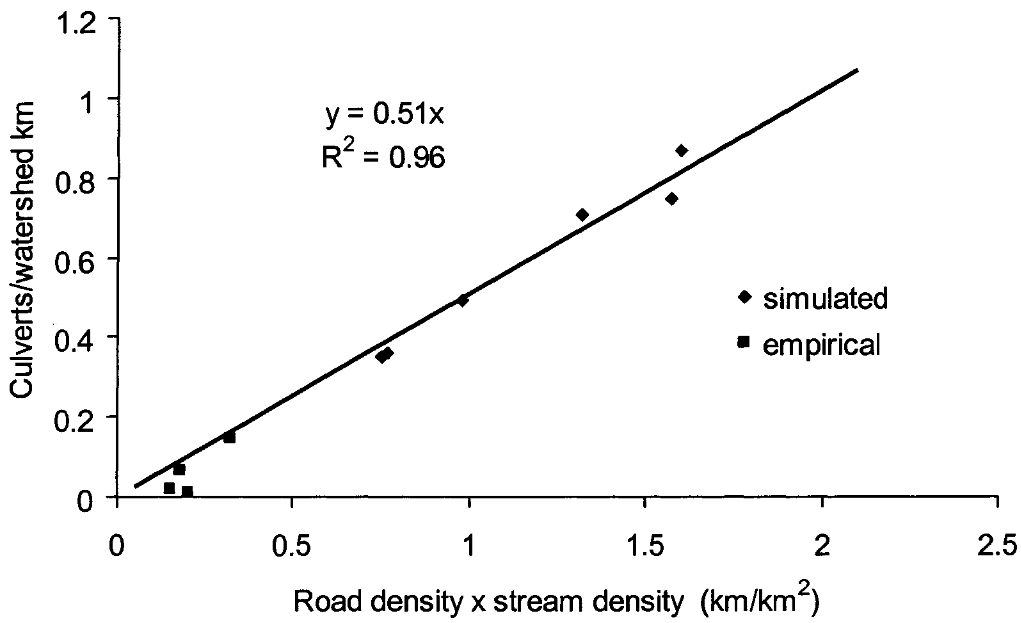

Figure 3.3. Relationship between road and stream density and density of culvert crossings derived from simulated GIS data depicted in ArcView, based on 100 km^2 sample blocks within study areas. Culverts were designated at the intersection of a 10 x 10 km road grid overlaid upon depicted watercourses of < order 5 classifications. Empirical data originated from spatial data analysis of northern Alberta watersheds (see Chapter 2).

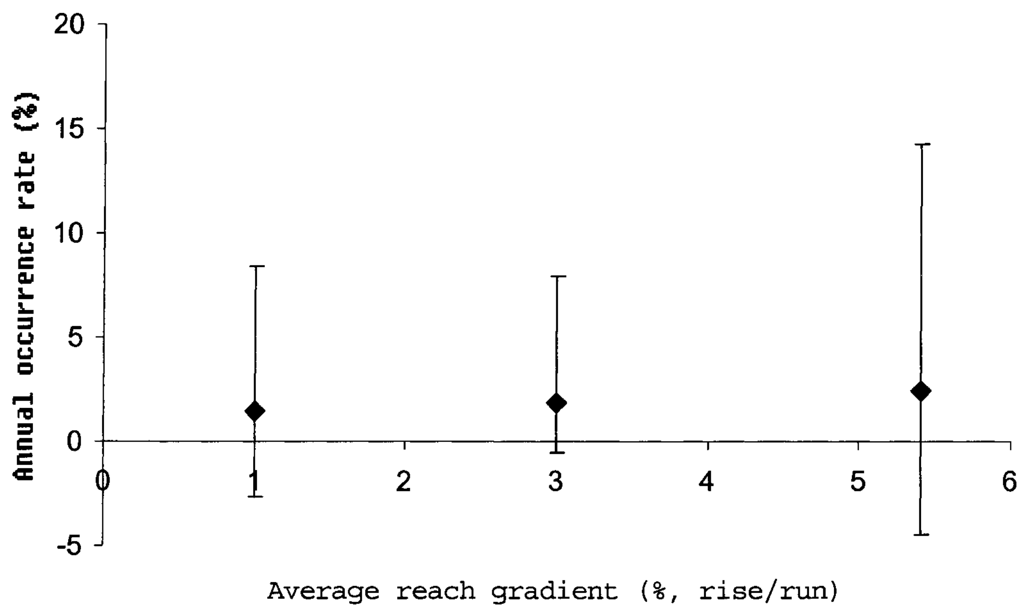

Figure 3.4. Relationship between average stream reach gradient and annual hanging culvert occurrence rate, showing 95% confidence intervals. Data originate from observational studies of hanging culverts and related variables in northern Alberta (Chapter 2). Annual hanging culvert occurrence rates are derived from linear regressions of culvert age vs. hanging culvert proportion in three gradient classes of landscapes, with the occurrence rate being the slope coefficient of the regression line for that gradient class.

Uncertainty

Uncertainty in HANGFRAG was quantified by two primary methods: user inputs, and variance within the key function of hanging culvert occurrence. Because each input parameter was user-defined (Table 3.1), the consequences of uncertainty around these parameters were quantified by running the model within ranges of reasonable variances around each parameter. The consequences of uncertainty in the function of annual culvert hang rate versus gradient were quantified by incorporating the observed statistical variance of the initial data set. This variance was calculated by first conducting a regression analysis within each gradient class (i.e., <2%, 2-4% and >4%) of proportion of hanging culverts by age-class. The slope coefficient of this relationship is the age-related hanging culvert occurrence rate, and an ANOVA test was used to derive its variance (Figure 3.4). From this variance, a normally distributed sample of 10,000 simulated slope coefficients was generated (using the Microsoft Excel random number generation function) for each of the three gradient classes. One slope from each gradient class was randomly chosen and regression statistics were derived. This technique was repeated 10,000 times and descriptive statistics were obtained for the sets of slopes and y-intercepts. The standard deviation for these two parameters was included in the functional equation in STELLA. The annual hanging culvert occurrence varied, following this distribution, around the mean, occasionally becoming negative. In reality, a negative failure rate is not possible. To correct for this, an "if-then" function was included in the model that converted a negative rate to zero, in effect creating a floor for the rate.

With this inherent variance, the robustness of HANGFRAG was assessed by comparing output trajectories. The model was considered to be robust at the required levels of discrimination if trajectories showed no or minimal overlap at simulation end, based on 10 trials at each different parameter set. Versions of the model were built with and without uncertainty or variance. While assessments of lever strength were not reported with variance, variance in HANGFRAG output was used to develop alternate scenarios that were robust (i.e., output values did not overlap).

Model Calibration

Business-as-usual (BAU) forecasts of my simulated watersheds were conducted initially to provide benchmarks against which to assess overall model function and evaluate variable performance. Forecast parameters were set to emulate conditions observed in focal areas presented in the previous chapter. Simulation results were evaluated based on both the time (years) to reach an arbitrary threshold of 75% contiguous small stream habitat and the percentage of contiguous habitat at the end of 100-year simulation periods.

Sensitivity analyses were performed using BAU forecasts as benchmarks to assess the relative power of manipulated variables to reduce fragmentation effects, with an emphasis on delaying or avoiding crossing the 75% threshold. The effect of variable changes on the rate and proportion of stream fragmentation was assessed by incrementally manipulating one variable at a time, holding all others at the benchmark values. Variable parameters were manipulated across the range of settings described in Table 3.1, by high, medium and low degrees. I quantified the sensitivity of incremental manipulations on model outcomes (i.e., reduction of time to threshold and fragmentation at 100 years) relative to the benchmark outcomes. Variables were ranked according to their relative effect. These analyses were performed with no model variance (i.e., no uncertainty).

Model Use

The HANGFRAG model was used to compare stream fragmentation and infrastructure costs (the cost of roads built and crossing structures culverts or installed and replaced) resulting from alternate road management strategies for simulated watersheds HILLS (high gradient) and PLAINS (low gradient) over a 100-year future time-span. The starting conditions used for conducting this comparison were structured according to a 2 by 2 matrix, differentiated by high and low landscape gradient with high and low levels of initial road impact. Thus, four landscape conditions were compared (Table 3.2). Topographic parameters (see Table 3.1) were set to emulate conditions observed in focal areas presented in the previous chapter.

Assessment of alternative management strategies in HANGFRAG was done by developing scenarios and comparing them against the BAU reference simulation for each landscape condition. Scenarios were developed that consisted of manipulated variables alone or in combination. Scenario development was constrained by the robustness of the model (i.e., no or minimal overlap of results at simulation end) and what I considered realistic and reasonable, based on a review of literature (i.e., Schneider 2002). Variables were set accordingly (Table 3.3). Strategies were evaluated relative to their effect on reducing fragmentation over time and infrastructure cost, and were compared on a low and high intervention level basis. I define intervention as the reduction of fragmentation.

Prior to scenario analyses, I developed arbitrary definitions of low and high intervention, and then applied those definitions consistently in all scenarios (see Table 3.3).

Relative financial costs ($/ road km, including crossings) of scenarios were also compared. The alternative cost of bridges-only stream crossing in all scenarios was reported for comparison. Results of scenarios were depicted showing variance, however variance is not otherwise reported. Unless specified, simulation results are reported at simulation end (100 years).

Results

Sensitivity Analyses

Comparisons of model response resulting from low, medium and high degrees of manipulation of variables indicated that culvert replacement had the strongest overall effect on reducing the rate of habitat fragmentation in both simulated watersheds (Table 3.4). The weakest lever was changing road location to avoid stream crossings. Manipulations of all variables had more relative effect on model output in the simulations of the less densely developed Watershed PLAINS.

Table 3.2. Two-by-two matrix of landscape conditions used to conduct HANGFRAG scenario analyses.

Initial Road Development Level	Landscape Gradient: Low (2.1%) →	High (3.4%)
Low (0.1 km/km^2) ↓	*Pristine Plains* low gradient low roads	*Pristine Hills* high gradient low roads
High (0.5 km/km^2)	*Developed Plains* low gradient high roads	*Developed Hills* high gradient high roads

Table 3.3. HANGFRAG culvert fragmentation model variables (management levers) manipulated in assessments of alterative road management strategies in simulated watersheds HILLS and PLAINS, showing settings for business-as-usual (BAU), low and high intervention scenarios. BAU equalled no intervention. Low intervention caused a delay in watershed fragmentation exceeding a threshold of 25%[a], and high intervention prevented exceeding the threshold during the 100-year simulation period, based on simulations of a 100 km^2 areal extent.

	Management Variable		
Scenario	Annual road build rate (%)	Road location[b]	Culvert replacement rate (n/yr/100km^2)
BAU	2	0.5	0
Low Intervention	2	0.5	0.1– 2
High Intervention	1.5	0.4	1 – 5

[a] Fragmented watershed = the proportion of <5[th] order stream reaches (km) located above hanging culverts.
[b]An index of the relative propensity of roads to cross streams (see text for definition). A value of 0.5 corresponds to random road location; the lower the value, the greater the avoidance of crossing streams.

Table 3.4. Results of assessment of relative strength of management levers in HANGFRAG model for business-as-usual (BAU) forecasts of simulated watersheds HILLS and PLAINS. Results are reported without variance.

Management Lever	Settings (low, med., high manipulations)	Model Response			
		Increase of years to threshold[a] (low to high)		Reduction in % fragmentation @ 100 years (low to high)	
		HILLS	PLAINS	HILLS	PLAINS
Road location [b]	0.45, 0.35, 0.25	0 – 4	1 – 16	0 – 3	2 – 9
Annual road build rate (%)	1.5, 1, 0.5	0	1 – 8	0 – 6	4 – 9
Culvert replacement (n/year/100km^2)	0.25, 0.5, 1	5 – 38	38 - ∞	0	9 – 41

[a] 25% habitat fragmented (km of streams in watershed located above hanging culverts).
[b] The relative propensity of roads to cross streams. A value of 0.5 is random (no avoidance or preference) with declining values indicating increasing avoidance.

Evaluation of Alternative Management Strategies

Between-watershed comparisons –The baseline trajectories of watershed fragmentation were similar for both Watershed PLAINS and Watershed HILLS (Figs. 3.5, 3.6, 3.7 and 3.8). However, intervention in Watershed HILLS generally required double the rate of culvert replacement compared to Watershed PLAINS (Table 3.5). The infrastructure cost of baseline and intervention scenarios was higher in the Watershed HILLS simulations (Table 3.6).

Low versus high intervention – Low intervention caused recovery (i.e. reduction in % fragmented) and postponed reaching the 25% fragmentation threshold until late in the 100-year time period (Figs. 3.5, 3.6, 3.7 and 3.8). High intervention caused recovery and prevented the threshold from being surpassed by 100 years. In some trials, high intervention scenarios caused recovery (i.e., increase in % accessible stream kms) that appeared sustainable beyond the time period. There was some overlap between high and low intervention trajectories prior to year 75, and they were indistinguishable prior to year 50.

Road Development Scenarios – At low initial road impact levels in both watersheds, intervention (avoidance of fragmentation) was achieved through culvert replacement alone (Table 3.5). In Watershed PLAINS, low intervention required culvert replacement at an annual rate of 0.1/100 km^2, with the high intervention rate increasing to 0.4. High intervention in Watershed HILLS required a tripling of culvert replacement rate (from 0.3 to 1.0). The cost of intervention strategies increased relative to baseline in low initial impact scenarios for both watersheds (Table 3.6).

Table 3.5. Settings of variable (management lever) of HANGFRAG business-as-usual (BAU) and fragmentation intervention scenarios of simulated watersheds HILLS (high gradient) and PLAINS (low gradient). Low intervention postponed reaching a 25% watershed fragmentation threshold until late in simulation period. High intervention prevented the threshold from being crossed during the simulation. Simulation period was 100 years, and areal extent was 100 km^2.

Scenario	Variable Setting		
	Culvert replacement rate (culverts/year/100km^2)	Annual road build rate (%)	Road location[a]
Watershed HILLS			
BAU baseline	0	2	0.5
Pristine HILLS			
Low intervention	0.3	2	0.5
High intervention	1	2	0.5
Developed HILLS			
Low intervention	2	2	0.5
High intervention	4	1.5	0.4
Watershed PLAINS			
BAU baseline	0	2	0.5
Pristine PLAINS			
Low intervention	0.1	2	0.5
High intervention	0.4	2	0.5
Developed PLAINS			
Low intervention	1	2	0.5
High intervention	2	1.5	0.4

[a] The relative propensity of roads to cross streams. A value of 0.5 is random (no avoidance or preference) with declining values indicating increasing avoidance.

Table 3.6. Costs of infrastructure[a] of HANGFRAG benchmark business-as-usual (BAU) forecasts[b], road development and remediation scenarios, with bridges-only alternative scenarios[c] for each, for simulated watersheds HILLS (high gradient) and PLAINS (low gradient). Results are reported without variance.

	Watershed HILLS			Watershed PLAINS		
	Baseline cost ($M)	Bridges-only cost ($M)	Cost change[d]	Baseline cost ($M)	Bridges-only cost ($M)	Cost change[d]
Road development (low initial road impact) scenarios						
Low impact baseline	1.9	2.9	+52.6%	1.9	2.5	+32%
Low impact/ low intervention	2.3	2.9	+26.1%	2.0	2.5	+25%
Low impact/ high intervention	3.2	2.9	-9.4%	2.5	2.5	0
Remediation (high initial road impact) scenarios						
High impact baseline	9.7	14.4	+49%	9.5	12.7	+34%
High impact/low intervention	12.2	14.4	+18%	10.8	12.7	+17.6%
High impact/high intervention	11.0	8.9	-19.1%	8.3	7.9	-4.8%

[a] Total cost of all roads and stream crossings during simulation.

[b] The infrastructure cost of forecast and remediation scenarios is the sum of road costs/km and culverts installed and replaced.

[c] The infrastructure cost of bridges only scenarios is the sum of road costs/km and all stream crossings installed (at a per unit rate of $40,000).

[d] Cost change of bridges-only relative to baseline simulation cost

Remediation Scenarios – At high levels of initial impact, intervention (reduction of fragmentation) required a 25% reduction of road build rate and an increase in the avoidance of stream crossings (parameter change of -20%) combined with varying rates of culvert replacement (Table 3.5). In both areas, high intervention required a doubling of the low intervention culvert replacement rate. In the high initial impact scenarios, the costs of intervention strategies, which consisted of varying degrees of road reduction, crossing avoidance and culvert replacement, varied relative to baseline (Table 3.6). For high gradient Watershed HILLS, low and high intervention ($12.2M and $11M, respectively) was more costly than baseline ($9.7M). In Watershed PLAINS, high intervention ($8.3M) was less costly than either low intervention or baseline, owing primarily to reduced road build rates.

Culverts vs. bridges cost comparison – The cost of bridges-only scenarios was higher than low intervention scenarios (Table 3.6). However, as intervention level increased to high, exclusive bridge use became less costly in all but one scenario (Watershed PLAINS, low initial impact), and in that case the cost was equal ($2.5M).

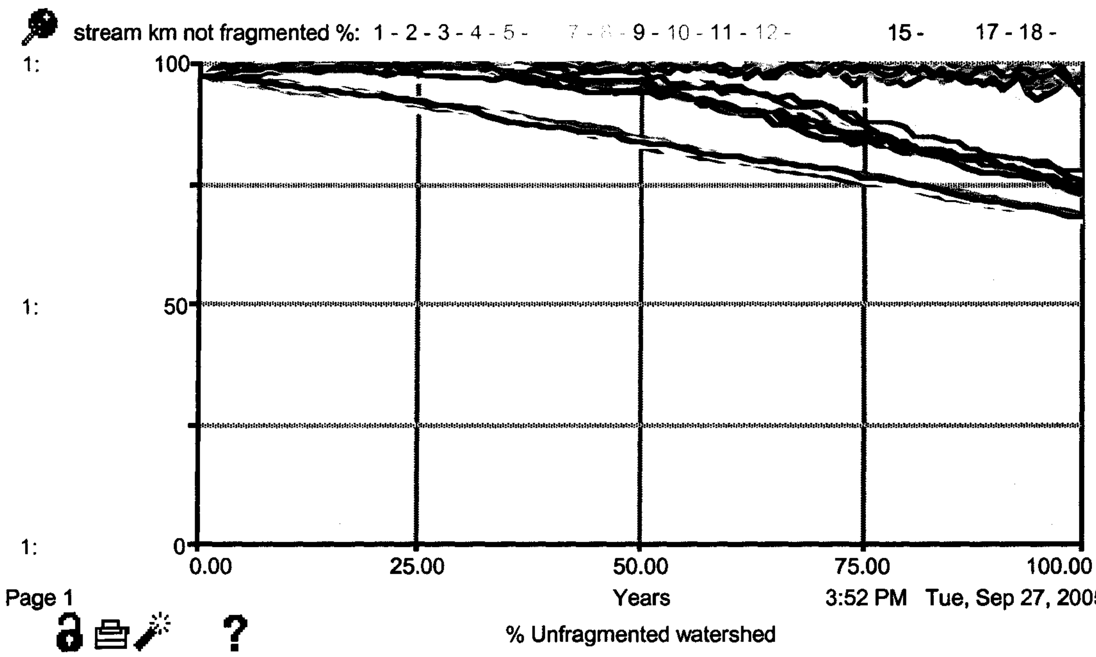

Figure 3.5. Comparative results of HANGFRAG simulations of low (middle cluster) and high (uppermost cluster) intervention level scenarios versus the business-as-usual baseline (lowest cluster) trajectory, for simulated Watershed HILLS at a low level of initial industrial development. Results depict variance and are based on 10 trials of model runs of each scenario.

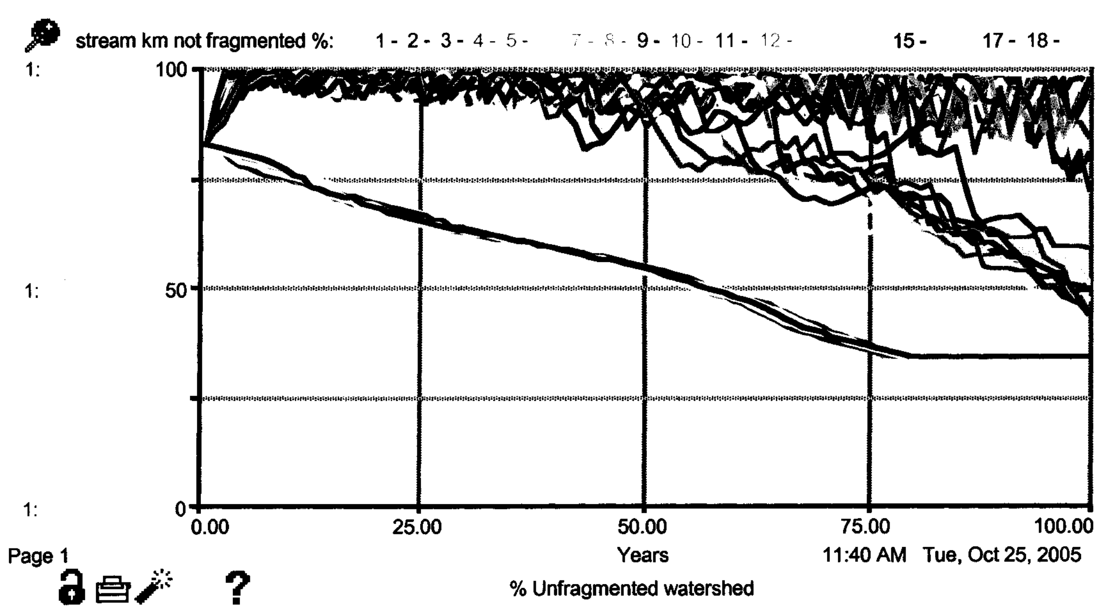

Figure 3.6. Comparative results of HANGFRAG simulations of low (middle cluster) and high (uppermost cluster) intervention level scenarios versus the business-as-usual baseline (lowest cluster) trajectory, for simulated Watershed HILLS at a high initial level of industrial development (i.e. remediation). Results depict variance and are based on 10 trials of model runs of each scenario.

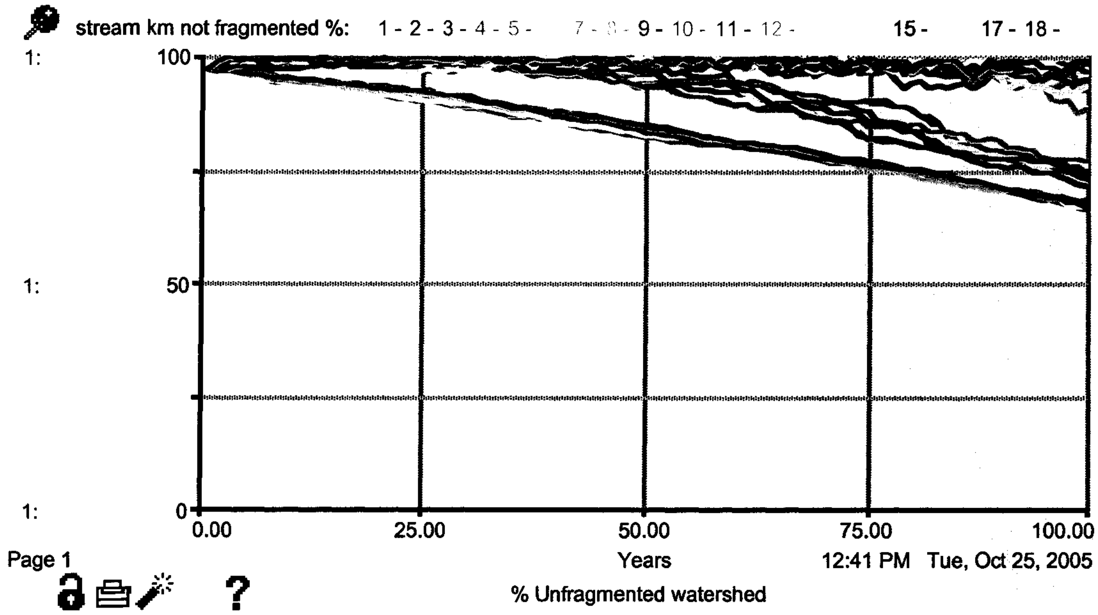

Figure 3.7. Comparative results of HANGFRAG simulations of low (middle cluster) and high (uppermost cluster) intervention level scenarios versus the business-as-usual baseline (lowest cluster) trajectory, for simulated Watershed PLAINS at a low level of initial industrial development. Results depict variance and are based on 10 trials of model runs of each scenario.

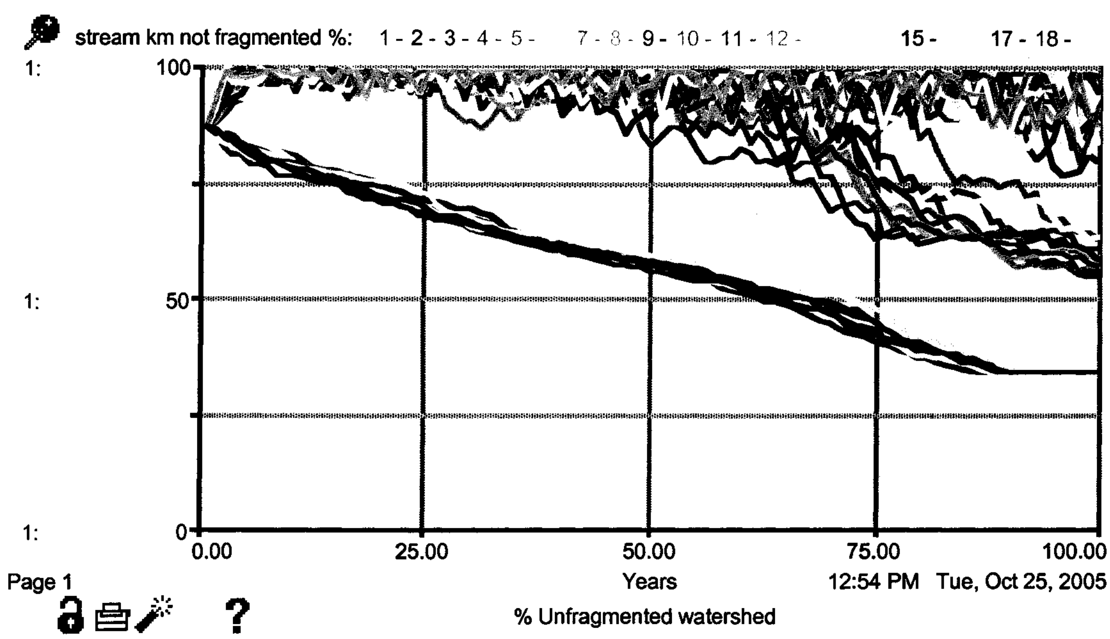

Figure 3.8. Comparative results of HANGFRAG simulations of low (middle cluster) and high (uppermost cluster) intervention level scenarios versus the business-as-usual baseline (lowest cluster) trajectory, for simulated Watershed PLAINS at a high initial level of industrial development (i.e. remediation). Results depict variance and are based on 10 trials of model runs of each scenario.

Discussion

The HANGFRAG model was sufficiently robust to permit comparison of low and high intervention scenarios near or at simulation end. However, uncertainty was sufficient to prevent distinction of low versus high intervention scenarios prior to year 50, and there was some overlap between trajectory clusters prior to year 75. Model output variance increased as parameter settings increased. There was clear distinction between forecasts and even low intervention scenarios throughout simulations, and the difference between forecasts and intervention trajectories was definite. The model provided clear indications of practices that may reduce hanging culvert-induced fragmentation and constitute best management.

I found that replacement of hanging culverts is a key management practice that can directly offset fragmentation effects. Even at low levels, replacement of hanging culverts can have a noticeable effect. Simulated model results support the conclusion from the previous chapter that culvert replacement was a likely cause of the negative relationship between culvert age and hanging culvert occurrence observed in the Notikewin River watershed. Although culvert replacement was a powerful remediation tool, high intervention required simulated decreases in annual road build rate and propensity to cross streams. This was not affected by landscape gradient.

Landscape gradient did affect the cost-effectiveness of culvert use versus pre-manufactured steel bridges. The use of bridges was relatively more cost-effective in the high versus low gradient situation; cost increases were either lower or reductions were greater. This effect was stronger for high intervention scenarios, where alternative use of bridges reduced long-term infrastructure costs by the greatest degree.

Despite the effect of gradient, culvert replacement was less costly than alternative bridges-only use, in scenarios of low intervention. The cost-advantage of culvert use, compared to bridges-only, decreased as the need to replace culverts and reduce road building increased. Best management plans may be based primarily on replacement of hanging culverts, however, if high levels of intervention are required in highly impacted areas, bridges-only use becomes cost-effective, retrospectively. This was particularly evident in high gradient watersheds. In order to prevent possible fragmentation of watersheds targeted by planned intensive road development, best long-term management plans should be based primarily on the use of bridges and minimizing road and stream crossing density.

A characteristic of high gradient watersheds is relatively high stream density. The result of this is higher crossing density per length of road and therefore increased per kilometer cost of road development compared to low gradient areas. Coupled with a higher rate of hanging culverts occurrence, this indicates a relative increase in potential fragmentation effect caused by a given length of road in high versus low gradient watersheds. The fragmentation risk related to road development and culvert use in high gradient watersheds is relatively high, as is the cost of mediating fragmentation effects.

The annual rate of road building was a sensitive parameter in simulations. Although the results of model simulations indicate that management strategies aimed at reducing culvert-induced stream fragmentation are most effective when they include high rates of culvert replacement, the effects of replacing culverts at a fixed number per year will be overwhelmed if annual road build rates exceed expected levels. This is reinforced by model results, which showed increasing fragmentation over time, given fixed culvert replacement rates. A comparison of low versus high intervention scenarios indicates that short-term results (at 25 years) are similar; however, a shift from low to high intervention is required to maintain low fragmentation as time passes and road density increases. Culvert replacement therefore needs to be positively linked to road density. Required rates of culvert replacement should be balanced with road development in order to achieve the results planned at the inception of an intervention strategy.

The benchmark forecast road build rate of 2% was both conservative and constant, which may not be expected in reality. Schneider (2002) predicted that the total length of roads in northeast Alberta would increase approximately 10-fold by the year 2050, representing an annual growth rate of approximately 9%. Although industrial activity and road development in Alberta's boreal forest is increasing overall, rates of development may differ considerably between years and watersheds, depending on current development and characteristics of existing road networks, specific hydrocarbon deposits and short and long-term corporate and government business plans. It is also reasonable to assume that annual road development rates in developing areas will decrease as the road network in an area becomes denser and access needs are met.

As an alternative to focusing solely on culvert replacement as a response to increasing road and culvert density, best management practices should include reduction of road development and avoidance of stream crossings, particularly if cost-reduction is desired. The observed decline in infrastructure cost from low to high intervention scenarios with culvert use is related to decreases of these variables. Road proliferation is related to varied road ownership between industrial corporations (Schneider 2002). If road use is not shared between owners, a multiplicity of roads may be built. Reducing the annual growth rate of roads may be realised by collaborative planning and shared road use between industrial corporations (Schneider 2002). At the same time, reducing the length of roads built will combine with stable or lower culvert replacement costs to yield a two-fold reduction in infrastructure investment. In model simulations, costs decreased as intervention increased despite higher culvert replacement, largely a result of decreased road construction. This is not without precedent. Schneider (2002) cites a pilot study in a $500km^2$ area in northeast Alberta, where forestry and petroleum industrial sectors collaborated to develop integrated road management plans. The results of the study indicated that road construction would decrease by 50%, saving $1.1 million over the time period in question. Managing road development for shared use and low growth rate will reduce costs and mitigate increasing need for culvert replacement.

Culvert replacement requires that the status of culverts be monitored rigorously. As a best management practice, monitoring and replacement must be combined. Alberta-Pacific Forest Products Inc. has adopted this practice in their Forest Management Area in northeast Alberta, monitoring culvert crossings and replacing hanging culverts observed on streams believed to support fish (Spafford, pers. comm.). Such action is likely the most beneficial first step that industrial corporations can make.

Restoring connectivity in heavily fragmented watersheds will require considerable effort, and restoration effort will increase exponentially as implementation of intervention strategies to reduce watershed fragmentation is delayed. The initial level of fragmentation of small streams in Watershed HILLS was nearly four times greater than in Watershed PLAINS. As a consequence, the treatment effort required for culvert replacement in simulations was 2 to 4 times higher and sustained over longer periods of time. Allowing hanging culverts to proliferate in a watershed not only causes ecological problems, but solving those problems requires more effort and cost. Remediation effort will also depend on the required immediacy of a response aimed at recovery of watershed integrity. Although a strategy of low levels of intervention caused a reduction of fragmentation in simulations, the rate of reduction was most rapid with high intervention.

A site-scale based analysis of costs of culverts and alternative crossings provides insight into the decision-making process at this scale and the resulting perpetuation of culvert use. Culvert replacement is roughly 2.5 times more costly than an original installation (Crawford, pers. comm.). Therefore, anticipated culvert replacement would be expected to be required at least 3 times during the life of a road in order to prompt a change in management to a less costly alternative. The typical cost of a temporary steel bridge is approximately 9 to10 times the cost of one culvert installation and 3 times the cost of a culvert replacement. At the local site scale, the use of a bridge is a financially favourable alternative only if anticipated culvert replacement is greater than 3 occurrences over the operational life of a road. However, at the watershed scale, simulated results indicate that the exclusive use of bridges is a cost-advantageous practice in high gradient watersheds, especially if hanging culvert-caused fragmentation is allowed to increase to degrees requiring high intervention. Further, the full financial cost attributed to culvert installation should include monitoring, replacement of hanging culverts, and risk of fines related to violation of regulations. The cost advantages of culverts versus bridges or avoiding crossing streams entirely would be reduced if such costs were included. Actions by regulatory agencies may be necessary to ensure that such actual costs are included in the operations of industrial road builders and to provide incentive to use bridges.

A weakness of this model is that some cost details are unknown and not included. For example, a modeled change in road location does not affect the road costs output. The relationship between road location (e.g., building roads on ridges versus near river plains) and cost was not modeled. Avoiding stream crossings reduces crossing costs, but may increase road density in an area. Costs related to culvert monitoring or bridge maintenance are not included in the model. Inclusion of such financial information would improve the utility of the model as a road-planning tool. Other costs related to hanging culvert occurrence, such as penalties and compensation for Canada Fisheries Act violations are not considered in this analysis. If culvert usage included these additional costs, any relative cost-advantage of culverts may be reduced to favour bridges or other alternative stream crossing practices. Other economic parameters, such as depreciated costs of assets, net present value, or alternate uses of funds saved by installing lower cost structures were not included. The consequences of including these factors are not clear and warrant further investigation.

There are other improvements that may be made to the HANGFRAG model to increase its utility. In particular, the road location function, which is entirely theoretical, lacks validation. Collection of empirical data from areas wherein either stream crossing avoidance or preference affects road location would be required to validate this relationship. It would also be useful to compare model results to comparable real-world situations (i.e., hanging culvert caused watershed fragmentation of boreal study areas not included in this study) as a means of assessing its predictive capability or accuracy.

The relationship between proportion of watershed fragmented and hanging culvert density provokes requires further investigation. It would be useful to validate the representation of the habitat fragmentation function by a logarithmic equation. The use of a logarithmic equation was based on my understanding that the proportion of watershed fragmented is not necessarily linearly related to hanging culvert density. The proportion of fragmented watershed caused by low densities of hanging culverts will be disproportionately great for barriers that occur on high order streams. One effect of this may be increasing variance in the fragmentation proportion at low values of barrier density. As hanging culvert density increases, the rate of habitat fragmentation may decline if additional hanging culverts are located above existing barriers. Variance must also decline. Maximum levels of fragmentation are reached when hanging culvert density is so high that additional hanging culverts are fragmenting already isolated stream segments, causing very little or no additional impact. The validation of this relationship and assessment of variance may be achieved by more extensive application of the method used to derive it.

Fragmentation amount is related to the stream order at the barrier site, as is the relative impact of the barrier upon the fish community. The diversity of fish communities in the boreal forest increases with stream width and order (Wootton 1990; Zwick 1992; Merkowsky 1998). It is likely that this relationship generally applies to all aquatic biota, following the ubiquitous species-area relationship that has fundamental importance in ecological science (Matter et al. 2002; Ovaskainen and Hanski 2003). Therefore, based on the number of species directly affected by a hanging culvert, the negative effects of fragmentation are also related to stream width and order. To facilitate an assessment and accounting of relative impact of fragmentation, or conversely, lost habitat values of fragmented stream reaches by order, a value weighting may be assigned to each order class. An overall index of the cost of fragmentation may be based on a summation of value-weighted lengths of fragmented stream reaches.

Fragmentation, however, does not necessarily result in loss of species in all situations. Even in a boreal environment, profoundly affected by environmental dynamics such as annual ice cover and periodic drought, populations of some organisms may persist above hanging culverts in fragmented stream segments. A dam on a large river may not necessarily cause the near-term extirpation of upstream fish populations; threats to population persistence in such circumstances are not immediate and are related to alteration of metapopulation dynamics, such as gene flow (Hanski 1998; Morita and Yamamoto 2002). On the other hand, first or second order streams may be regularly barren of fishes following major perturbations. Movement barriers along these streams prevent species' reinvasion of upper reaches, effectively eliminating them as habitat. Following MacArthur and Wilson's (1967) concept of island biogeography, fragmented stream reaches may be viewed as islands, with the likelihood of persistence of fragmented populations over time increasing as fragment size increases. A useful framework for assessing landscape-scale fragmentation effects and planning remediation may be based on an order-based risk of extirpation and the relative habitat value of stream reaches, along with parameters quantifying the occurrence of hanging culverts and consequent amount of habitat fragmented (e.g. proportions of barriers and average km of stream fragmented) by stream order class.

Conclusions

The business-as-usual approach to road and culvert management will result in increasing habitat fragmentation of small boreal streams over time in Alberta. Allowing hanging culverts to proliferate causes increased fragmentation, risk of ecological problems and accumulated potential financial obligation. Fragmentation caused by hanging culverts may be mediated primarily by culvert replacement, but may also require a reduction in road build rates and avoidance of stream crossings if high intervention levels are required. Culvert use and replacement is cost-effective if road density is low or low intervention is required. This is particularly true in low gradient areas. Increasing gradient decreases the cost-advantage of culvert use. High road density or high levels of intervention reverse the cost relationship, favouring the use of pre-manufactured steel bridges.

The use of culverts is perpetuated by relatively low costs when decisions are limited to the scale of the site in question and a relatively small temporal outlook; however, analysis of the true financial cost of culvert usage should include consideration of landscape gradient, potential hanging culvert occurrence rates, and include monitoring and replacement of hanging culverts and risk of fines related to violation of regulations, particularly over long (>50 year) time spans. The cost advantage of culverts would be reduced if such considerations were included. Reduction of cost advantage would favour adoption of alternative management strategies. Less tangible costs of culverts include the impact of watershed fragmentation on biotic communities. Actions by regulatory agencies may be necessary to ensure that such costs are included in the operations of industrial road builders. Decisions regarding culvert use should be made at the watershed scale to facilitate best management.

Management actions are required to avert increasing watershed fragmentation caused by hanging culverts. Intervention strategies should be implemented to offset or eliminate the occurrence rate of hanging culverts. The trajectory of restoration of watershed connectivity depends on the level of intervention. That trajectory, in turn, is based on the goals of land users and resource managers.

Chapter 4 – Ecological and strategic implications of boreal stream fragmentation

Business-as-usual (BAU) road management practices have resulted in the occurrence of hanging culverts at stream crossings along industrial roads in Alberta's boreal forest. These barriers are causing watersheds to be fragmented with respect to fish movement. If the forecasted BAU trajectory (i.e., increasing levels of road and culvert construction causing exponentially increasing stream fragmentation) is not altered, the ecological effects of extensive fragmentation of watersheds may threaten the persistence of fish and other lotic species inhabiting small boreal streams. In the second chapter of this thesis, I quantified the occurrence of hanging culverts in focal areas in northern Alberta, their age and occurrence rates over time, and related these rates to relevant attributes of culverts and their physical setting. I also quantified the fragmentation of watersheds arising from hanging culverts. In the third chapter, I used this information to construct a simulation model of hanging culvert fragmentation (HANGFRAG) to forecast and subsequently evaluate alternative road crossing management strategies. In this chapter, I follow that work by placing stream fragmentation into a theoretical ecological context, in order to better understand its ecological implications and develop a large-scale strategic approach to restore and maintain watershed connectivity.

To further understand the ecological implications of fragmentation of streams, I considered a conceptual model based on MacArthur and Wilson's (1967) theory of island biogeography and the species-area relationship commonly applied in ecology (Matter et al. 2002; Ovaskainen and Hanski 2003). MacArthur and Wilson's (1967) model (Figure 4.1) describes the combined effects of island size and proximity to mainland in regulating immigration and extirpation rates and, ultimately, species diversity. According to their model, rates of extirpation decrease as island size increases. Immigration rate increases as proximity to mainland decreases. Large islands, close to a mainland, support larger, more diverse communities of species than do small, remote islands.

My conceptual model considers stream fragments isolated by barriers to be analogous to MacArthur and Wilson's islands. Barriers (e.g., hanging culverts) restrict or block upstream travel of fishes to these fragments. The hierarchical nature of stream networks is an important factor in understanding ecological implications of stream habitat fragmentation. Boreal stream networks are typically arranged in a dendritic pattern on the landscape, coalescing and concentrating flow into fewer, larger channels. For this reason, streams generally increase in size (i.e. volume, width) with stream order, or relative position in the watershed network, and distance from headwaters (Zorn et al. 2002). As stream size and order increase, habitat area (analogous to island size) must also therefore increase.

The conceptual framework I propose is similar to the classic island biogeography model in terms of the inverse relationship between island (or fragment) size and species extirpation rates. In a fragmented stream, the ability of isolated segments to support animal populations is determined by their size or stream order, which, although variable, is closely related (see chapter 2). In the context of watersheds in the boreal forest, natural events such as winterkill, fires, droughts, and floods are primary factors affecting stream organisms (Schneider 2002; Dunham et al. 2003; Lake 2003), particularly fishes. From the perspective of fishes, such events are important in creating local, perhaps seasonal extinctions. Habitat conditions in small, low-order streams that are more sensitive to these factors are therefore less stable (Schlosser 1990). Populations of fishes residing in small streams are therefore more prone to extirpation caused by extremely variable conditions. For example, small boreal streams that nearly or completely freeze to the bottom may become barren of fish in winter, yet fish would persist in higher-order, deeper streams lower in the same watershed. This habitat-size related persistence is likely the reason for observations of higher fish species diversity in large versus small streams (Merkowsky 1998; Zorn et al. 2002). This variable ability of streams to support species can be viewed in terms of MacArthur and Wilson's extirpation rate. In my framework, based on fishes, annual extirpation probability is related to fragment size. Winter is the primary natural disturbance, with drought secondary. The annual probability of extirpation of fishes in the smallest streams is high and declines as stream order increases. Large streams or rivers are very resistant to environmental extremes; however, species persistence here may be regulated by other less immediate factors, such as disease and reduced gene flow (Morita and Yamamoto 2002). The effects of such factors are generally slower, resulting in a low annual extirpation risk.

In my framework, immigration rates are related to the density of downstream barriers. In its simplest form, with hanging culverts completely blocking upstream movement, immigration to upstream fragments is functionally null (analogous to MacArthur and Wilson's model with lowest rates of immigration, or the most remote islands possible).

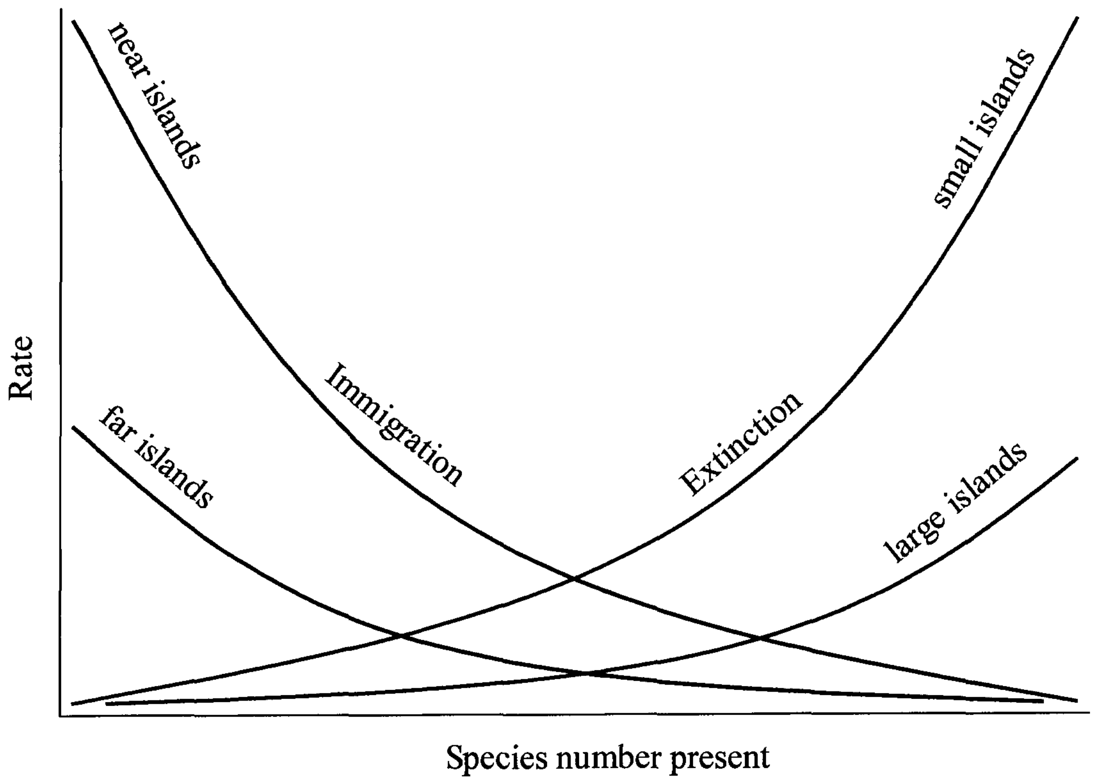

Figure 4.1. Equilibrium model of biotas of islands of varying size and distance from principal source area (after MacArthur and Wilson 1967).

Following this framework, the ecological consequence of watershed fragmentation is therefore the loss of fish species within watershed fragments, proximately mediated by natural disturbance events. This effect is inversely proportional to stream size, increasing as stream size decreases. If barriers to immigration remain, the habitats remain unavailable. This is a one-way trajectory of habitat loss over time, with the rate of loss dependent on the frequency and severity of disturbances and the density of barriers.

Although the most direct effects of such habitat fragmentation and loss will be to fishes, a broader array of effects may arise. Through trophic cascade mechanisms (Carpenter and Kitchell 1993), the loss of a single species may have an inverse effect on species at adjacent trophic levels, and may also initiate a series of effects that ripple though ecological systems, perhaps even altering energy pathways in community food webs. Top-down regulation of aquatic systems by fishes is well documented (Martin et al. 1992; Ruetz et al. 2002). As a theoretical example of this in boreal streams, a decline in Arctic grayling (*Thymallus arcticus*) and white sucker (*Catostomus commersonii*) populations in fragmented stream reaches may lead to local increases in benthic grazing invertebrates, which may in turn result in reduced algal density and increased conversion of detritus to invertebrate biomass. Given the downstream flow of nutrients, the resulting changes to nutrient pathways could affect communities of organisms in habitats not otherwise directly affected by fragmentation.

The effects of trophic cascade are potentially far-reaching and not predictable or consistent (Carpenter et al. 2001; Wootton 2004). In their meta-analysis of trophic cascade, Brett and Goldman (1996) identified considerable variation in the response of zooplankton and phytoplankton to changes in fish populations. Once trophic cascade effects occur, they may persist in a new alternative state of equilibrium, which resists change and efforts designed to recreate the former condition (Chase 2004). The potential inability to predict or undo anthropogenic-caused trophic cascade effects at various scales should prompt ecologists and resource managers to adopt a liberal approach when predicting or assessing the ecological implications of watershed fragmentation, and a conservative, precautionary approach to land use planning.

Remediation, or prevention, of fragmentation, may be planned to minimize ecological consequences. The HANGFRAG model indicated that the most powerful single remediative tool is hanging culvert replacement. Strategically, culvert replacement should be planned to generate the maximum benefit. Based on the preceding theoretical framework, I have built a simple model describing the effects of culvert replacement at the watershed scale (Figure 4.2). A logical preventative approach is to avoid the use of culverts in certain situations. In a proactive context, this model can be directly applied to guide the prevention of fragmentation via avoidance of culvert usage

The presentation of my model begins with the discussion of its components and how it was developed. As with MacArthur and Wilson's model, my model is largely based on the inverse relationship between habitat (i.e. stream fragment) size and extirpation rate of fishes. I used annual extirpation rate as a parameter, assigning the values shown in Figure 4.2 for each order class. I derived these values somewhat arbitrarily, basing them on my intuitive assessment of extirpation caused primarily by annual ice formation and to a lesser extent by seasonal dewatering and drought. The other parameters in the remediation model are designed to capture the relative quantity of fragmented stream habitats. I used the average size (km) of fragmented stream by order class, akin to island size. The proportion of stream fragments occurring in a watershed, by order class, represented the relative distribution of stream fragment quantities. The values of these parameters, as shown, are based on empirical data obtained from the field studies and modeling described in the preceding chapters. An output curve was the product of all three parameters, for each order class of stream affected by fragmentation in the hypothetical watershed. This product was scaled out of 100.

The resulting curve represents the relative value of lost, fragmented habitat by stream order at the watershed scale. Given the parameter values used, the greatest severity or value of habitat loss is associated with order 2 streams. Therefore, at the watershed scale, eliminating or avoiding barriers on all order 2 streams would, would restore or prevent the loss of the largest relative value of habitat. From a financial perspective, this also implies that dollars allocated towards watershed remediation would best be applied to order 2 streams.

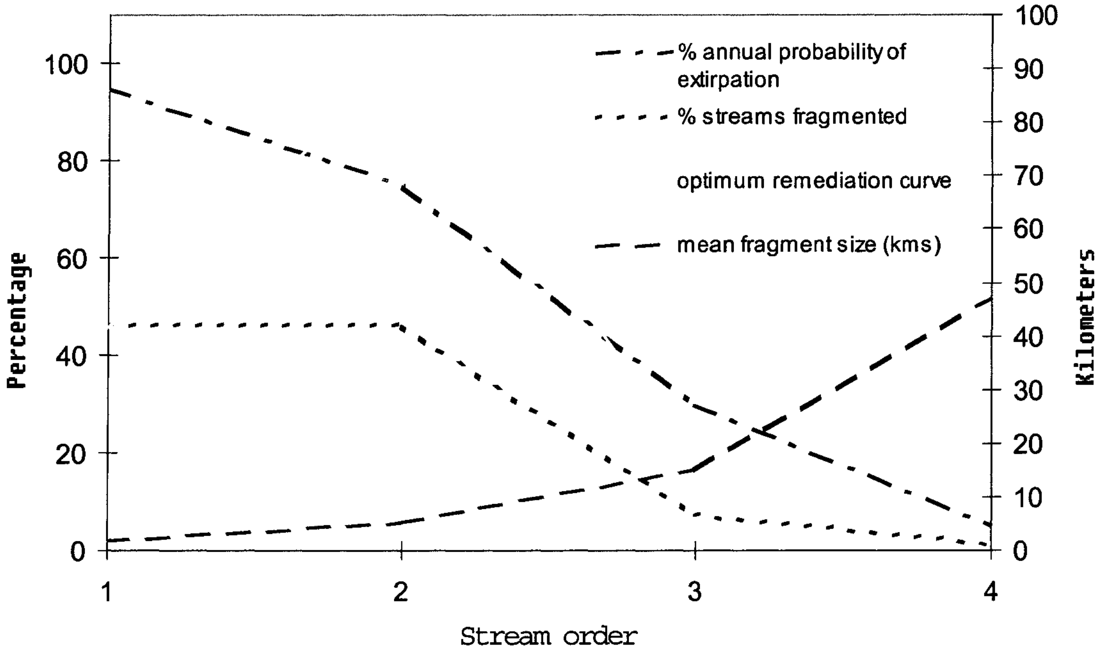

Figure 4.2. Watershed-level fragmentation remediation model, showing optimal remediation curve. The remediation curve value for each stream order class is generated by multiplying the values of all other parameters. Mean fragment size (kms) is assigned to the secondary y-axis. All other values are assigned to the primary y-axis (%).

Of course, this model is theoretical. The model component most in need of validation is the annual extirpation rate, or conversely, the relative ability of stream order classes to support a broad complement of fishes extant in the watershed, specific habitat requirements notwithstanding. Given this, the validation of the optimum remediation curve may be furthered via a comparison of fish species presence in fragmented stream reaches, by order class, before and at time intervals after the removal of the barriers. The expected result would be a persistent greater diversity of fish species in higher order restored fragments. This information, combined with an accounting of the relevant spatial data parameters, would represent an empirical model that may be compared to the theoretical model I have presented.

Culvert replacement is not entirely benign, and has more than financial cost. The removal and reinstallation of culverts requires the use of heavy machinery and earthwork. The disturbance of the culvert site brings a risk of increased streambank erosion and silt loading, as well as temporary displacement of organisms. Increased sediment input has well documented negative effects on stream biota (Newcombe and Macdonald 1991; Waters 1995). The ecological consequences of increased sediment loading caused by culvert replacement may be relatively minor and ephemeral, in comparison to fragmentation effects, but should not be dismissed, particularly if several culverts are replaced on a common watercourse in a concise time period. Under these circumstances, effects may be acute and pose an immediate threat to species. The effects of sediment move downstream and coalesce, accumulating and readily combining with other conditions that threaten stream ecosystems, such as drought or high water temperature. Sediment intrusion at disturbed stream crossing sites should be minimized. The timing of replacement activities should be set in consideration of cumulative effects, stream flow regimes and important biological time periods (e.g. fish spawning). Assuming culvert replacement costs are more or less equal across between order classes, the curve represents the optimum point of gain in a cost-benefit analysis, and provides a means to apportion remediation efforts so that the negative effects of offset by maximizing benefit.

Despite the potential economic and ecological problems associated with culvert replacement, barriers must be eliminated if watershed fragmentation is to be reduced. The accumulated number of hanging culverts present in Alberta's boreal forest makes remediation costly, both ecologically and economically. The task can be made more manageable and beneficial by adopting a strategic planning approach, such as the one I have presented. In a proactive and preventative context, the discontinuation of culverts to cross perhaps all but intermittent streams is the surest way to ensure that watershed fragmentation caused by hanging culverts ceases to threaten the persistence of boreal stream communities.

Summary

Key results of this research are the identification and quantification of the development of hanging culverts and consequent watershed fragmentation over time. Each new culvert installed on the landscape adds to the number of potentially hanging culverts and increases fragmentation risk. I suggest that it is reasonable to view all culverts as hanging culverts, in the same way that all children are geriatrics, provided they persist long enough. Stream dynamics and the process of culvert ageing indicate that all culverts will be hanging in the future; it is just a matter of time. Culverts are static, but a stream is not. Given that, culverts are inappropriate structures for long-term or permanent road crossings over natural watercourses that support communities of organisms, particularly fishes existing in the unproductive and relatively harsh boreal landscape.

Avoiding the use of culverts, or replacing them before they become hanging, can circumvent the ageing process. Best road management practices are aimed at doing this, and management strategies may consist of a suite of practices. The choice between alternative road management strategies is made in consideration of time span, cost-effectiveness, and ecological conservation goals. Factors such as landscape gradient affect hanging culvert occurrence rates, and determine the relative cost-effectiveness of different road management strategies. Ideally, for maintaining ecological integrity, cost-effectiveness and conservation goals must be viewed over the long-term.

Fragmentation caused by hanging culverts is a growing threat to boreal aquatic ecosystems. Fragmentation reduces habitat area and alters aquatic community structure, with generally negative effects that may be unpredictable and magnified via trophic cascade. Remediation of culvert-fragmented watersheds is required to reduce the risk of such events in Alberta's boreal forest. Remediation and alternatives to culverts are costly, but should be considered the cost of sustainable industrial activity in the boreal forest. Regulatory agencies and the public in general should act to provide incentives to adopt road management practices that minimize or eliminate fragmentation. Steps such as culvert marking and inventory, monitoring and record-keeping should be combined with law enforcement tools.

In addition to remediation, more information is needed to more definitively resolve the process of hanging culvert development and their effects on fish movement and aquatic communities. Future research should focus on more definitive resolution of the culvert age vs. hanging outfall occurrence relationship, facilitated by marking and monitoring of culverts in order to eliminate the potential for replaced culverts to mask age effects. The role of culvert diameter in mediating the culvert age- hanging culvert occurrence process should be resolved. Very large culverts, well-exceeding stream channel width may be a reasonable and cost-effective alternative to traditional culverts and bridges, if adequately installed and maintained. The assessment and monitoring of large diameter culverts over sufficient time periods is necessary. The effects of hanging culverts in restricting fish movement, and possibly that of other organisms, need to be quantified and related to outfall hang height and other variables. Organism distributions and abundances are the truest indicators of movement constraints. Studies should be done to quantify aquatic communities above and below culverts and hanging culverts, with a particular focus on identifying potential trophic cascade effects. As mentioned in

Chapter 4, diversity of fishes and perhaps other aquatic organisms should also be related to stream order classes in a diversity of boreal settings.

The business-as-usual trajectory is not necessarily the path of the future. Culverts need not be permanent fixtures on the boreal landscape, and hanging culverts need not occur. The adoption of best road management practices would result in culvert-induced fragmentation becoming a historical footnote in the story of human interaction with the boreal forest ecosystem.

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