Identifying and prioritizing barriers to Atlantic salmon habitat connectivity in Napu'saqnuk (St Mary's River), Mi'kma'ki (Nova Scotia, Canada)

By

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ABSTRACT

Atlantic salmon (*Salmo salar*) are an anadromous fish species that migrate from headwaters of their home rivers out to the open ocean and back; this ecologically, economically, and culturally significant species requires extensive and well-connected freshwater habitat to successfully reproduce and maintain viable populations. However, the installation of road culverts can fragment aquatic habitat and impede Atlantic salmon from reaching their spawning grounds. In mainland Nova Scotia, Napu'saqnuk, known as the St. Mary's River, represents important habitat for a population of Atlantic salmon that has been assessed as 'Endangered.' Removing and remediating culverts that cause habitat fragmentation in the area is therefore of utmost importance, however it can be time and resource intensive. Through field assessments in the West Branch of the river over the summer of 2023 I collected data on 75 culverts' abilities to successfully pass Atlantic salmon and general information on their structure and state of function. I have combined this information with remotely collected landscape scale characteristics of each site to further investigate the relationship between culvert characteristics and passability. Logistic regression modelling identified the characteristics of shape, diameter, change in elevation, and position in the watershed to be the best predictors of a culvert being able to successfully pass salmon. The results of field assessments indicated that the river continues to experience severe fragmentation, with 77% of culverts assessed to be a partial or full barrier to fish passage. Culverts previously recommended for remediation by the St Mary's River Association in 2009 were revisited to find some had been removed or modified; other sites continue to be legacy barriers potentially fragmenting the watershed habitat for up to several decades. Using collected data on fish passage and estimated upstream habitat, I prioritized additional sites in the West Branch for further assessment and remediation. My research provides a framework for future culvert assessments and remediation in this important watershed by leveraging data collected through a combination of fieldwork and remote sensing.

Keywords: *culvert, Atlantic salmon, Salmo salar, aquatic habitat connectivity, freshwater*

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I am an uninvited guest on the unsurrended land of the Mi'kmaq. What is now known as Nova Scotia's entire land base lies within Mi'kma'ki. Since time immemorial the Mi'kmaq have been the stewards of this land. The degree of habitat fragmentation which my paper investigates did not occur in Mi'kma'ki before colonization. I am grateful to learn and live here and recognize that we are all treaty people. Thank you to my co-supervisors, Dr. Alana Westwood and Ben Collison for your ongoing support and guidance throughout this project. Thank you again to my co-supervisors and to Revant Sharan for contributing to my data collection efforts over the 2023 field season. Bushwhacking through dense brush to crawl through a big metal tube filled with stagnant water is a lot more enjoyable in good company. I would like to thank the Nova Scotia Salmon Association for providing training on culvert assessments before we began our field surveys. Thank you, Dr. Tarah Wright for your constant positivity and support in every honours seminar. I'd like to thank my family for their encouragement throughout this process and my friends for their support, patience, and quite possibly feigned interest in culverts.

CHAPTER 1 – INTRODUCTION

1.1 Motivation

From Napu'saqnuk (the St Mary's River)'s shallow soil springs black spruce, red spruce, and white pine. On the drumlins and slopes of the watershed's rolling hills are tolerant hardwood forests and through the West Branch's floodplains and wetlands endangered species like the mainland moose and wood turtle find refuge (Nova Scotia Department of Lands and Forestry, 2019). With 62% of the ecodistrict being Crown land, there is little urban development in the watershed, and most economic activity is driven by resource extraction; namely forestry (Nova Scotia Department of Lands and Forestry, 2019). But Napu'saqnuk has more to offer than the extraction of its natural resources. Conservation organizations like the Nova Scotia Nature Trust (NSNT) and the St Mary's River Association (SMRA) are dedicated to protecting this watershed and restoring habitat previously lost. As of 2024, NSNT has acquired 9 square kilometres of conservation land across Napu'saqnuk (St Mary's River, 2024). Beloved by conservationists and recreators alike, the area has long been a popular spot for angling trout and the famous Atlantic salmon.

The St. Mary's River watershed provides essential habitat for Atlantic salmon (*Salmo salar*) (Nova Scotia Department of Lands and Forestry, 2019; Fisheries and Oceans Canada [DFO], 2013) who provide ecosystem services like nutrient transportation and serve as a food source for larger terrestrial vertebrates among other roles in freshwater ecosystems (Gibson et al., 2011; Willson & Halupka, 1995). Populations of wild Atlantic salmon in Nova Scotia's Southern Upland designatable unit (DU) have been assessed as 'Endangered' by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC, 2010), with the St. Mary's River being identified as one of the last rivers in mainland Nova Scotia where stocks have stayed relatively stable over the last decade (DFO, 2009). The watershed is also actively undergoing feasibility analyses by DFO, with multiple partners, for one of Canada's first Ecologically Significant Area (ESA) designations. ESAs are an area-based regulatory tool underpinned by s. 35.2 of the *Fisheries Act* to provide "long-term enhanced conservation and protection of key areas for fish and fish habitat that are highly productive, sensitive, rare, and/or unique and to ensure effective restoration of these areas when restoration is needed" (DFO, 2023). As home to one of the last viable populations in mainland Nova Scotia, the St.

Mary's River system presents an opportunity to conserve river-run Atlantic salmon in the region and is therefore a priority for conservation and restoration.

The rivers and streams of the St. Mary's River watershed are disrupted by poorly designed, installed, and maintained culverts that fragment its streams (Hunter & Mitchell, 2013; Mitchell, 2010). Culvert removal and remediation has been found to be one of the most effective restoration techniques for high-quality fish habitat (Erkinaro et al., 2017; Roni et al., 2002). To preserve and restore habitat connectivity in the St Mary's River it is necessary to better understand how culverts may be impacting freshwater habitat connectivity so that new installations are well designed and take into consideration how different types of culverts can negatively impact salmon passability. Guiding my research was my goal was to inform future installation practices, provide methods to identify possible problem culverts, and to prioritize current barriers to connectivity in the watershed for remediation.

1.2 Background

Habitat connectivity refers to the degree to which landscapes allow for the movement and migration of species within and between habitats, therefore aquatic habitat connectivity is the degree to which rivers and streams can allow aquatic organisms and abiotic material to move freely through the water network (McGarigal & Cushman, 2002; Ormerod et al., 2011). This allows for key activities like foraging, migration, and exchange of genetic material to occur and for environmental processes like the transport of sediment to continue undisturbed (Lehrter et al., 2024; Poplar-Jeffers et al., 2008; Wofford et al., 2005). As an anadromous species, salmon are especially dependent on aquatic habitat connectivity to travel the long distances between the ocean and their home river's headwaters where their spawning grounds are often located.

The installation of infrastructure at road and stream intersections is a common barrier to aquatic connectivity (Frankiewicz et al., 2021). This infrastructure is often a bridge or a culvert. A culvert is a pipe or similar structure, installed under and perpendicular to a road, through which water can flow; they are commonly installed as an alternative to a bridge due to lower cost and suitability to transport water for smaller streams (Mitchell, 2010). While many culverts are used to mitigate the impacts of flooding from irregularly high-water levels, they are also installed when a road is built over an existing perennial (flowing continuously throughout the year) stream.

The ability for culverts to successfully pass fish can be impacted by both landscape and site level characteristics. To increase efficiency of identifying culverts for remediation, studies have calculated culvert slopes (site or local scale) using remotely sensed data (landscape scale) (Arsenault et al., 2022). A landscape-level characteristic refers to a landscape as a geographic area where said characteristics vary through space. This area can be a watershed, a country, or other area whose delineation can based on ecological, geographic, or administrative units that align with the stated research and objected (Wu, 2013). A digital elevation model (DEM) can be derived using LiDAR (Light Detection and Ranging) data which utilizes laser pulses from an aircraft to measure distances. The elevation information held within the DEM is landscape-level characteristic. The characteristics and information which make up the unique profile of each culvert are all local scale, including a culvert's length, diameter, age, material, and shape.

In 2009, SMRA performed 99 stream crossing assessments in the watershed (Mitchell, 2010). Culverts were identified either as a barrier to connectivity or as passable for Atlantic salmon based on established threshold for criteria related to passability such as water depth, outflow drops, and water velocity.

1.3 Introduction to study

Through my research, I aimed to improve the current understanding of Atlantic salmon habitat connectivity in the St. Mary's River watershed through a combination of field data collection, desktop analysis, and statistical modelling. More specifically, my goal was to identify which culvert characteristics impact Atlantic salmon passage, and by how much. This can be summarized by my research questions:

1. What is the current state of freshwater habitat connectivity for Atlantic salmon through road culverts in the St Mary's River watershed?
2. What local and landscape scale characteristics are predictive of culvert passability for Atlantic salmon?
3. Can some of these characteristics (length, slope) be determined through desktop analysis?
4. What culverts in the West Branch of the Napu'saqnuk should be prioritized for further study and remediation?

CHAPTER 2 – LITERATURE REVIEW

2.1 The Atlantic Salmon

The Atlantic salmon (*Salmo salar*), or plamu ("blah-moo") in Mi'kmaw, is a member of the Salmonidae family, which includes the species of pacific salmon found on the West coast of Canada (*Oncorhynchus spp.)* among other salmonids that we do not call "salmon" such as trout and char. Salmonids, in fact, are comprised of around 70 cold water mid-level predatory species (Davidson, 2013; Mills, 2001). Unlike the 5 pacific salmon species *Oncorhynchus spp.* who die shortly after spawning (Schindler et al., 2003), the Atlantic salmon is known to survive and complete its migration and spawning process multiple times (Gibson et al., 2011). The Atlantic salmon has a unique life cycle (Table 2.1) that necessitates ample and well-connected freshwater habitat. The species is anadromous, meaning it travels from the ocean to freshwater to spawn.

Born in freshwater after incubating as embryos in gravel streambeds, Atlantic salmon will remain for 2 to 4 years before migrating to the open ocean (Hansen & Quinn, 1998).

Table 2.1 Atlantic salmon life stages

Life Stage	Description
Egg	Fertilized eggs laid in gravel nests (redds)
Alevin	Hatched eggs with yolk sac attached
Fry	Absorbed yolk sac, distinct appearance of a fish
Parr	Markings develop, camouflage for river environment
Smolt	Transitioning for saltwater adaptation, silver color
Kelt	After spawning, return to the ocean

The length of ocean residency where salmon hunt capelin, herring and other sea life varies among populations and individuals. Generally, after 1 to 5 years, a salmon will reach maturity and begin its return to freshwater to spawn (Hansen & Quinn, 1998). This migration connects the survival of stocks to the presence of streams that that are suitable for the activities of spawning, foraging, and overall survival. As an anadromous species, a basic requirement for population survival is the ability to move freely from the estuary to spawning areas upstream for sexually mature adults and vice versa for smolts who are migrating towards the open ocean (Bardonnet & Baglinière, 2011). Habitat favourable for spawning can range from the top of the intertidal zone up to the headwaters of large rivers and the latter case spawners must migrate distances of up to 700 kilometres to reach their redds (nest where salmon eggs are deposited) (Bardonnet & Baglinière, 2011). To successfully travel these long distances, Atlantic salmon require an expansive and connected stream network. While there is no single sequence of movements or timeline that characterizes all populations of the Atlantic salmon, a constant necessity for the species is the ability move between different habitat types to fulfill all stages of their life cycle.

2.2 Atlantic salmon populations in Mi'kma'ki and Napu'saqnuk

Atlantic salmon are at risk globally and locally, with populations in decline across many maritime rivers. Human activity in the Americas during and post colonization has dramatically affected salmon populations through activities including ocean overfishing and the pollution, destruction, acidification, and fragmentation of their freshwater habitat (Parrish et al., 1998; Thorstad et al., 2021). Populations of wild Atlantic salmon in Nova Scotia's Southern Upland designatable unit (DU) have been assessed as 'Endangered' by COSEWIC (COSEWIC, 2010). Within this DU, there are 63 rivers known to have supported Atlantic salmon populations in the recent past, representing 9% of all rivers in Canada known to support the species (Gibson et al., 2011). Anecdotal data from recreational fishing is consistent with annual abundance data from four rivers within the DU that show declines of 83% to 99% since peak recorded levels in the 1980s (Gibson et al., 2011). In its 2010 report, COSEWIC names the LaHave and St Mary's rivers as the two populations in the DU that may be viable under current conditions (COSEWIC, 2010).

Within the Southern Upland DU, Salmon Fishing Area 20 (SFA 20) represents the Eastern Shore including the St. Mary's River watershed. DFO (2009) assessed the state of populations within this SFA using the West Branch of the St. Mary's River as the index population. This study observed the first significant increase in escapement (proportion of salmon successfully migrating to spawning grounds) in 5 years, however this value is still only 23% of what is considered to be the conservation requirement for the West Branch (DFO, 2009). While the results of this study reveal the circumstances to be relatively dire, it does indicate that populations may not be continuing to deteriorate and could even be improving. Furthermore, the November 2024 COSEWIC status update for Atlantic salmon will split the Southern Uplands into two new DUs with distinct evolutionary significance (Lehnert et al., 2023a). It is anticipated that the St. Mary's River will continue to be the index population monitored for the revised Southern Uplands – East DU (Lehnert et al., 2023b). The Southern Upland population and many other DUs have been "under consideration" for listing under the *Species At Risk Act* (SARA) since the last assessment was completed nearly 15 years ago (COSEWIC, 2010). The effectiveness of SARA at accomplishing its objective of recovering species at risk of extinction has been subject to debate in the peer-reviewed literature (e.g., Bird & Hodges, 2017; Creighton & Bennett, 2019; Turcotte et al., 2021; Montgomery et al., 2021), and local non-governmental organizations have been opposed to a SARA listing for Atlantic salmon in the St. Mary's River (Bruce, 2021). The influence that the upcoming COSEWIC re-assessment, diverging DU structure, and SARA listing decision (if there is one) has on future priorities of addressing salmon recovery threats in the watershed remains to be seen.

In recent years, there has been substantial investment in conservation and restoration work on the St. Mary's River specifically targeting Atlantic salmon and their habitat. In 2019, a collaboration of government departments and ministries announced the Nova Scotia Salmon Association (NSSA) and the St. Mary's River Association (SMRA) would jointly receive up to $1.8 million through the Oceans Protection Plan towards watershed restoration in eastern Nova Scotia (DFO, 2019). Much of this work is focused on habitat restoration in the West Branch of the St. Mary's River for species that require both freshwater and coastal habitat throughout their life history like the Atlantic salmon, among others (DFO, 2019; *St. Mary's River Association Projects*, 2021). While the species has experienced massive declines since the beginning of colonization, the St. Mary's River is home to one of the most stable populations in mainland Nova Scotia and presents an opportunity to conserve river-run Atlantic salmon in the region where conservation and restoration initiatives are already established and relatively well funded.

2.3 Habitat connectivity – fragmented and restored

Salmon rely heavily on river systems for migration and spawning (Bardonnet & Baglinière, 2011) and are therefore dependent on aquatic habitat connectivity as they must be able to travel a long and uninterrupted distance from the ocean through river networks to small freshwater streams to successfully reproduce. Relatively little is understood about aquatic habitat connectivity in comparison to terrestrial habitat (Park et al., 2008), however aquatic fragmentation has been identified as a factor impacting Atlantic salmon populations' ability to successfully spawn in the province's watersheds (Gibson et al., 2011). Freshwater habitat connectivity is fragmented by anthropogenic activity like hydroelectric projects, the installation of infrastructure at stream crossings, and cumulative effect of ecosystem changes; all of which cause negative impacts to Atlantic salmon populations (Cameron et al., 2009).

Culverts installed at road crossings can restrict the movement and migration patterns of fish by blocking mature fish from returning to spawning habitat, keeping juvenile fish upstream where resources are limited, and generally infringing on the mobility necessary to complete survival activities (Warren & Pardew, 1998). The blockage of fish passage at culverts results in loss of spawning habitat upstream, fragmented species distributions, and genetic isolation thus reducing overall population productivity (Burford et al., 2009; Wofford et al., 2005). Combined with additional anthropogenic stressors like warming stream temperatures, invasive species, and increased predation, habitat fragmentation is a significant contributor to population declines and can be compounded by multiple culvert installations within the same stream (Diebel et al., 2015; Parrish et al., 1998).

However, this lost habitat and its associated services can be recovered. Culvert remediation can increase accessibility of important habitat for salmonids to use for spawning, foraging, and thermal refugia (Erkinaro et al., 2017; Knoth et al., 2022; Poplar-Jeffers et al., 2008; Wilbur et al., 2020). For these reasons, restoring connectivity of habitat isolated by in-stream anthropogenic barriers is a priority in watershed restoration that often brings about quick improvements in populations with a relatively high success rate when suitable upstream habitat exists (Hill et al., 2019; Erkinaro et al., 2017; Roni et al., 2002). Due to culverts' significant impact on aquatic connectivity they continue to be a focus for habitat improvement in freshwater systems (Anderson et al., 2012; Arsenault et al., 2022) as recommended by Roni et al (2002). Therefore, while culverts can have large negative impacts on habitat connectivity, habitat restoration through removal and remediation has been proven to be effective.

2.4 What is a culvert and what makes it a barrier?

The *Guidelines for the Design of Fish Passage for Culverts in Nova Scotia* define a culvert as "a watercourse crossing structure with or without an invert on which rests an embankment that serves as a foundation for the road (in contrast to a bridge, which does not require an embankment)" (DFO, 2015). Physical characteristics like material, shape, and dimension of culverts vary greatly, with commonly used materials being corrugated metal, wood, concrete, and polyvinyl chloride (PVC) and shapes like box, circular, and arch (Mitchell, 2010). These large tubes which streams flow through under roads are ubiquitous on Nova Scotia's vast network of resource roads, and are often the preferred form of infrastructure due to their low cost and quick installation time relative to bridges (Mitchell, 2010). While they are often placed in smaller streams than bridges and dams, their impact is outsized and can be even greater than that of larger infrastructure due to their cumulative abundance (Diebel et al., 2015; Januchowski- Hartley et al., 2014) and when poorly designed and installed they pose a threat to aquatic ecology and should therefore be studied and remediated when possible.

Generally, fish passage can be assessed through different criteria including: (1) the presence/absence of an outflow drop (where the bottom of the culvert is not submerged in the stream at the outflow, causing a waterfall effect which will often impede fish passage), (2) the slope along which the culvert runs, (3) depth of water within the culvert, and (4) velocity at which water flows through the culvert (Dane, 1978; Mitchell, 2010; Poplar-Jeffers et al., 2008). Whether a culvert causes aquatic fragmentation depends on its ability to pass fish from one side to another. However, the ability for fish to pass through culverts varies greatly by species and life cycle stage (Peake, 2008) as it is dependent on their swimming performance. A minimum water depth of 0.20-0.23 meters is required for Atlantic salmon to pass through structures successfully (Adams & Whyte, 1990; Dane, 1978; Mitchell, 2010). Further depth considerations include the depth of the plunge pool at the culvert's outflow (Belford & Gould, 1989; Cahoon et al., 2007; Warren & Pardew, 1998) and tailwater depth (Peake, 2008) while steeper slopes pose more of a challenge for individuals to swim up and through.

Previous work by the St. Mary's River Association (SMRA) has used a conservative estimation of slopes greater than 0.5% being a barrier to passage (Mitchell, 2010). In Nova Scotia and New Brunswick, culverts installed with a slope greater than 0.5% may require the installation of baffled culverts (Arsenault et al., 2022; DFO, 2015) however other studies have identified the maximum threshold for adult Atlantic salmon passage to be 4% (Bourne et al., 2011). The slope and water depth of a culvert will directly impact the velocity at which water flows through it. The faster that water flows downstream through the culvert, the more resistance individuals encounter swimming upstream. The threshold in-culvert water velocities identified for adult salmon was 0.90 m/s for culverts greater than 24.4 m in length and 1.2 m/s for culverts shorter than that (Peake, 2008). For parr, the threshold velocity identified was 0.3 m/s (Adams & Whyte, 1990; Dane, 1978; Peake 2008, Mitchell, 2010). Additional considerations for evaluation of passability include amount of refuge from high velocity within and near the culvert (Belford & Gould, 1989; Lehrter et al., 2024; Warren & Pardew, 1998). Embedded or open bottom culverts allow for the natural stream substrate to continue throughout the length of the culvert and slow down flow creating a calmer aquatic environment (DFO, 2015; Lehrter et al., 2024).

The quantification of passability itself can be but is not limited to a binary (passable/barrier), a tiered categorization (passable/partial barrier/barrier), or as a scale of 0 to 1 when based on the proportion of fish able to pass through while migrating upstream used in observational studies, among other methods (O'Hanley & Tomberlin, 2005). While there are a range of values generally agreed upon in the literature for Atlantic salmon passability thresholds, when assessing a physical structure for passability outflow drop and slope are used as indicators of velocity. These thresholds have been identified for species of significance such as the Atlantic salmon although it is important to note that passability is complex and real thresholds can vary with individuals' fitness, life history, and circumstance (Cahoon et al., 2007).

2.5 Culverts in Napu'saqnuk

The prevalence of forestry activity means that logging roads often intersect the St. Mary's River watershed leading to the presence of an estimated 2,000 culverts, of which an estimated one third to one half likely have passage issues (Hunter & Mitchell, 2013). The most recent broad-scale culvert assessment for passability occurred in 2009 when 99 culverts across the watershed were surveyed by the SMRA. Of the 99 culverts assessed, 62 were deemed to be installed in streams that were fish habitat. Of this subsample, 40 culverts had a water depth of less than 0.20 m and 24 had an outflow drop (Mitchell, 2010). Further research by the SMRA has estimated costs to be $50,000 per culvert replacement and $5,000 per culvert mitigation project. With these estimates, a total overhaul of barrier culverts in the watershed would cost approximately $11.8 million and take between 30 and 50 years (Hunter & Mitchel, 2013).

Systematic prioritization based on barrier severity, culvert location on the road and river network, and prescribed mitigation strategy could significantly reduce the expenses and resources associated with such a large undertaking. Selecting culverts whose mitigation will yield the greatest returns is an effective method to streamline habitat restoration and achieve rapid results (Kemp & O'Hanley, 2010; Maitland et al., 2016; Roni et al., 2002). With the last comprehensive survey completed nearly 15 years ago, there is a large gap in understanding the current state of habitat connectivity in the St. Mary's River. Due to prohibitive costs of restoration, is important to develop methods that allow restoration teams to target culverts whose removal or remediation will have the greatest impact. It is equally important to better understand what design characteristics may lead to culverts being a barrier to better inform future installation decisions.

2.6 Predicting passage

Previous studies have used varying criteria and methods to assess and predict culvert passability with success. First, fish passage success at culverts was established to be lower than at other crossings through mark-recapture and observational studies. This same research found that general fish movement at all types of crossings was inversely related to water velocities observed as well as the ratio of velocity to depth (Warren & Pardew, 1998). Further modelling found that found slope, slope x length, and water velocity were all negatively correlated with salmonid passability and were ground truthed through mark-recapture field work at 26 road- crossings (Coffman, 2005). Research in 2014 used the presence of culvert outflow drops and water velocity as predictors of passability for migratory fish (Januchowski-Hartley et al., 2014). Independent variables in the models used included upstream area draining to the culvert, slope at the culvert, and stream gradient. This use of modelling using known, landscape scale information such as drainage area to inform local characteristics like the velocity at the culvert demonstrates how models can be used to identify potential barrier culverts before assessing them in the field.

Specifically, regression is a statistically proven method to identify factors that influence culvert passability and highlight its applicability as a predictor of which culverts will be barriers (O'Hanley & Kemp, 2010), however a major disadvantage to this method is its requirement of passability data of a large sample of culverts, information on the characteristics being studied, and knowledge of threshold values for target species (Warren & Pardew, 1998; Coffman 2005; Kemp & O'Hanley, 2010). Among other physical characteristics, culvert slope has been used to assess passability and have been used to successfully predict passability when a field validated sample is available. Statistical modelling informed by data recorded on the ground and previously established knowledge on fish passage can be an affordable method to prioritize culverts for further investigation, remediation, or removal. While these physical parameters were found to be useful for guiding further study and to inform field surveys, there are no models that include variables like shape, material, and dimensions for predicting passability. While these local scale characteristics have not been used to predict passability and thus to identify potential barriers, studies have identified certain structural characteristics to be more conducive to passability than others.

Undersized culverts have been found to impact passage by concentrating flow (Frankiewicz et al., 2021; Langill & Zamora, 2002) thus creating velocities above target species thresholds. Identifying undersized installations to be associated with the accumulation of debris, Frankiewicz et al. (2021) recommended that culvert width is at minimum the average width of the stream bed in which it is installed. Similarly, for culvert installations in Nova Scotia DFO recommends a minimum diameter of 1 m if installed in fish habitat (DFO, 2015). Like large culverts, open bottom designs have been identified to facility passage better than their closed counterparts for a variety of target species (Lehrter et al., 2024; MacDonald & Davies, 2007; Warren & Pardew, 1998), likely due to constriction of velocity which can impact even the strongest of swimmers. The need for natural stream substrate within the structure to slow fast moving flows and assist with backwatering has been identified in scientific studies and installation guidelines (DFO, 2015; Johnson et al., 2019; Rodgers et al., 2017; Warren & Pardew, 1998). If landscape scale information retrieved from elevation and watershed data can be combined with available local scale characteristics such as a culverts size and shape, predictions can be made on passability and thus streamline field assessment and help inform prioritized removals.

2.7 Remote sensing to inform passability

Spatial datasets are important inputs for aquatic fragmentation analysis and can be used to inform studies on culvert passability and create more efficient framework for assessment combining remote analysis and field assessments (Kemp & O'Hanley, 2010). Field assessments of 2,235 culverts in the Great Lakes were used to inform regression models that found upstream drainage area to be the most important predictor of velocity, and stream segment gradient the most important predictor of an outflow drop (Januchowski-Hartley et al., 2014). This type of model is helpful when considering broad-scale prioritization of barrier removal using landscape scale information to restore ecological connectivity. Building on this concept, a LiDAR derived digital elevation model (DEM) can be used as a landscape scale variable to accurately predict the slopes at individual culverts (Arsenault et al., 2022). This framework was used to assess stream connectivity and examine fish passability via predicted length and slope measurements for culverts throughout the Restigouche River watershed in eastern New Brunswick using a LiDAR derived DEM, high resolution orthophotography, and publicly available road and stream network data (Arsenault et al., 2022). While such methods cannot provide a complete picture of individual culvert functionality, they can be used as a tool to shorten workflow for prioritizing sites to assess in person (Arsenault et al., 2022; Erkinaro et al., 2017).

Field validation is an important component to this research as it builds trust in the models created by confirming their accuracy. This is an important step to refine methods and models, thus allowing them to better describe and predict reality. In studies of culvert passability, assessments are based on a combination of set criteria determined through previously compiled research, and the subjective assessment of the field crew present (Kemp & O'Hanley, 2010). The inherent subjectivity of culvert assessments injects potential for error into data collected for field validation. However, it remains an important tool to inform the creation of models and to assess the validity of predictions. The comparison of predicted outcomes to observations can improve our understanding of passability and lead to methods and models that better suit and describe connectivity.

Slopes recorded on the ground using a Zip Level were used to validate the estimations for 78 culverts derived from LiDAR DEM by Arsenault et al (2022). The results of this field validation demonstrate the accuracy and applicability of Arsenault's methodology with no statistically significant difference between estimates and ground-truthed measurements (Arsenault et al., 2022). Field validation contributes to a more accurate, comprehensive, and robust model that can use landscape scale information to predict the state of passability at individual sites.

CHAPTER 3 – METHODS

3.1 Study Area

The West Branch of the St Mary's River runs about 56 km and drains 470 km^2 of land, while the entire river's watershed is 1350 km^2 (Figure 3.1; Hunter & Mitchell, 2013). The river is within the ecodistrict that bears its name, which encompasses 850 km^2. Of this area, 4% is comprised of surface freshwater (Nova Scotia Department of Lands and Forestry, 2019). This includes the extensive network of watercourses flowing north-to south that feed the West Branch of the river. Like the rest of the province, the climate in the study area is cool with average monthly temperatures ranging from -6.0 degrees Celsius in January to 18.4 degrees Celsius in August and regular rainfall throughout the year. Monthly rainfall has a mean of 112.1 mm and during winter a monthly mean snowfall of 14.3 cm (Mitchell, 2009).

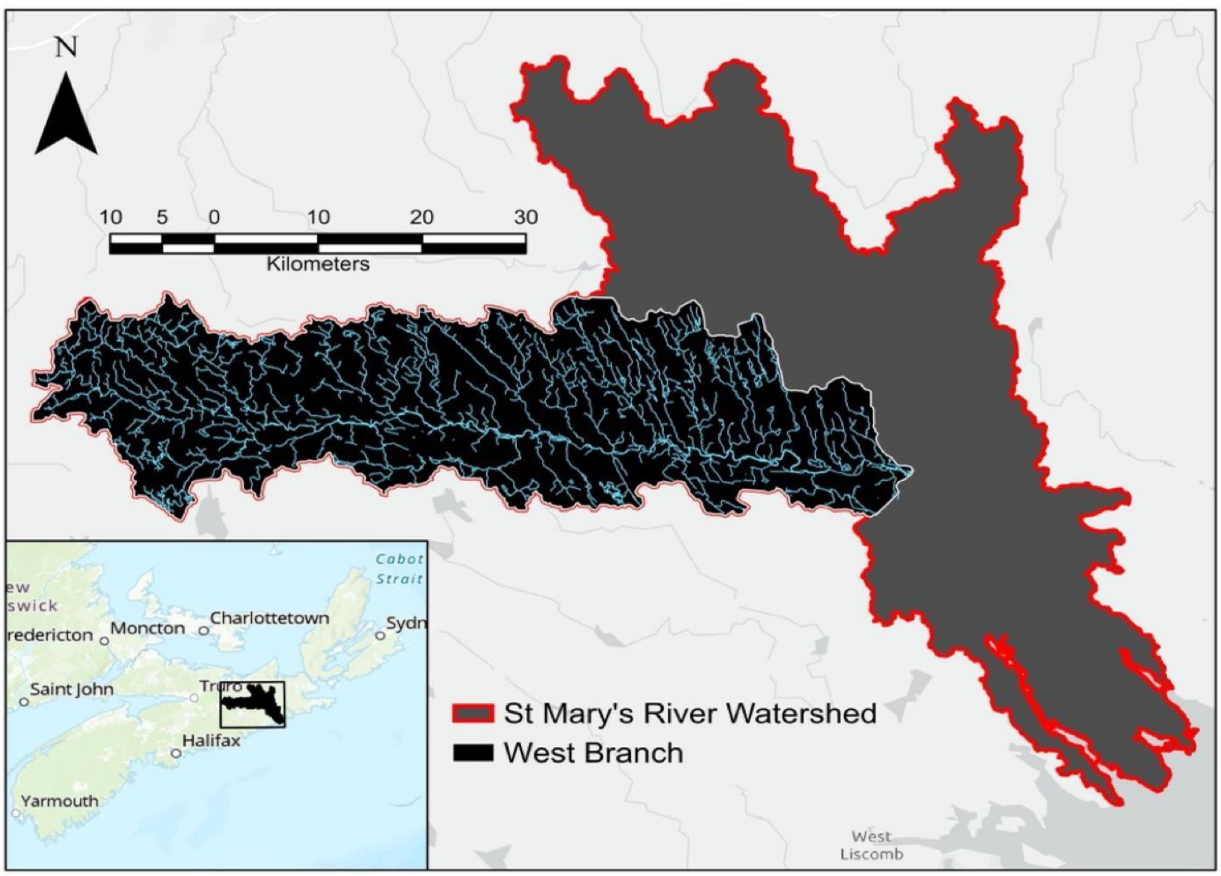


Figure 3.1 Map of the St Mary's River / Napu'saqnuk watershed

Much of the previously settled areas in the ecodistrict have reverted to forest that are mainly mid-successional and highly fragmented (Nova Scotia Department of Lands and Forestry, 2019). Of the Crown land in the ecodistrict 81% is classified for general resources use (C1) by the Integrated Resources Management (IRM) classification (Nova Scotia Department of Lands and Forestry, 2019). Forestry is the dominant resource use activity on both Crown and private land, with the majority of Crown land under the license and management of Port Hawkesbury Paper (Port Hawkesbury Paper, 2022).

3.2 Culvert sampling

I sampled culverts in the West Branch for passability by Atlantic salmon over the period of June 22 to July 14, 2023. Culverts sampled in the West Branch were selected using a non- probabilistic sampling method based on available information and field conditions. Culverts previously assessed by the SMRA and/or the NSSA made up 13 sites of the sites visited, and previously un-assessed culverts were also located and assessed when possible. Using publicly the available provincial road and stream network data (Table 3.1) points of intersection of these two layers where no bridge was known to occur were identified on ArcGIS Pro Version 3.2.1 (ESRI Inc., 2023) as a potential culvert location.

Table 3.1 Spatial Data

Name	Description	Year	Resolution	Citation
Nova Scotia Topographic DataBase – Water Features (Poly Layer)	Surface water pool of the St Mary's River	2023	Vector (Polygon)	NSTDB (2023a)
1:10,000 Nova Scotia Sub-Tertiary Watersheds	Boundaries of tributary catchments within the West Branch	2021	Vector (Polygon)	NSTDB (2021)
1:10,000 Nova Scotia Orthophotography	Geometrically corrected images taken on 24/08/2018 and 20/09/2019		0.2 m	NSODB (2019)
Nova Scotia Topographic DataBase – Water Features (Line Layer)	Surface water flow of the St Mary's River	2023	Vector (Line)	NSTDB (2023b)
NSTDB Roads, Trails and Rails (Line Layer)	Road network	2023	Vector (Line)	NSTDB (2023c)
NSTDB Roads, Trails and Rails (Break Line Layer)	Road network used to identify bridges and culverts	2023	Vector (Line)	NSTDB (2023d)
St Mary's DEM	Nova Scotia Salmon Association and the Applied Geomatics Research Group (AGRG) at Nova Scotia Community College	2021	2 m	NSCC & NSSA (2021)
SMRA Previously Assessed	SMRA 2009 culvert survey: fieldwork done by SMRA, digitized layer created by Fish and Fish Habitat Protection Program, Fisheries and Oceans Canada	2020	Vector (Point)	DFO & SMRA (2020)

Using 1:10,000 orthophotography available through the province (NSODB 2021) and other open-source imagery, the presence of culverts and general accessibility was assessed visually. Potential culverts were sorted into the categories of primary, secondary, and tertiary sites based on their position in the stream network (Figure 3.2). Culverts located near the main stem of the river with no known barrier between them were classified as primary, while sites immediately upstream to them were classified as secondary. Culverts closer to the top of the network with multiple other sites downstream of them were identified as tertiary sites. This classification was useful to plan the sequence of culvert assessments that ensured significant time was not spent assessing culverts upstream of a barrier. After primary sites had been visited, secondary and tertiary sites upstream of known primary sites assessed to be barriers were deprioritized from the sampling plan. This system made efficient use of time in the field where we had large distances to cover each day.

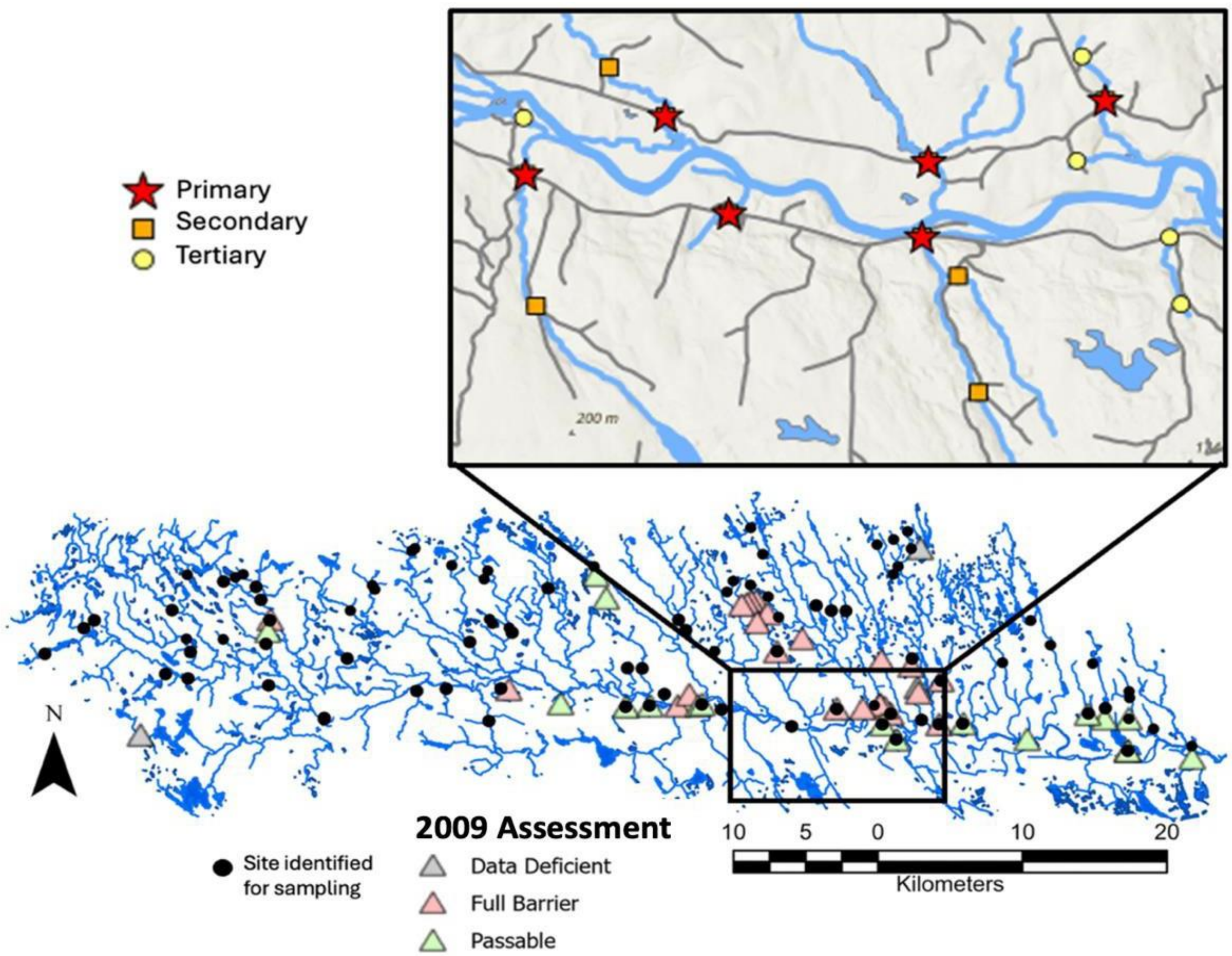


Figure 3.2 Map of sites identified for sampling

The nature of the study area meant most fieldwork required travel and work on remote resource roads in areas with active logging operations. Some roads were blocked by downed trees or were completely grown over and out of use. Where this was the case, we continued on foot for up to around 800 metres to access sites, depending on the conditions of the road. Sites where a culvert was predicted by the road and stream layers but not found were noted and removed from the sample.

3.3 Field Assessment

Over the field season 104 culverts were visited and 75 were deemed to be fish habitat (Table 3.2). This decision was made considering riparian areas, substrate, flow, and stream morphology. Water temperature was measured sporadically using a YSI handheld water quality meter at 15 of these 75 sites between June 22nd and July 14th. Temperatures ranging between

12.7 and 20.2 with a mean of 15.9 degrees Celsius. While 20 degrees Celsius is at or slightly above the upper threshold for longer exposures, these temperatures recorded in peak summer correspond to suitable temperatures for both juvenile and adult Atlantic salmon (Breau, 2013; Peake 2008).

Table 3.2 Culverts sampled

Classification	Culverts visited (n=104)	Fish habitat (n=75)
Primary	26	17
Secondary	23	19
Tertiary	55	39

Each culvert was assessed to be either passable, a partial barrier, or a barrier fish passage and all characteristics were recorded. This determination was informed by the NSSA’s culvert assessment field sheet (Appendix A). First, the four questions that comprise a rapid assessment were answered (Figure 3.3):

1. Is there a visible outflow drop?
2. Is water depth less than 15 cm in at least one location inside culvert?
3. Is the culvert not fully backwatered?
4. Is the stream width noticeably different above and below the culvert?

Figure 3.3 Culverts corresponding to rapid assessment criteria

The model organism these criteria are based on is a spawning Atlantic salmon returning from the ocean. Like other salmonids, the Atlantic salmon have evolved to endure long and challenging migrations and are therefore strong swimmers and jumpers (Peake, 2008). Studies suggest a conservative maximum water velocities of 0.9 to 1.2 m/s within a culvert for the Atlantic salmon to successfully swim through (Peake, 2008). These established baselines inform rapid assessments used for salmon passage established by different watershed groups including the NSSA. Therefore, a culvert that is passable using the metrics identified by the NSSA is by no means passable to all fish found in the area, some of whom require very different conditions than the Atlantic salmon. For example, another species of conservation priority found in the watershed is the American eel (COSEWIC, 2012). The American eel has a suggested threshold velocity of 0.2 m/s and is unable to jump thus making the considerations for passability very different for this species (Peake ,2008).

Next, culvert characteristics such as material, shape, current state of deterioration, entrance type, and dimensions (Figure 3.4) were recorded, and the locations of all culverts assessed in the field were recorded using a Garmin GPS unit.

Figure 3.4 Culverts visited in Napu'saqnuk

3.4 Remote sensing and field validation

The length and slope of each culvert assessed for passability over the field season was estimated using a simplified remote sensing method demonstrated by Arsenault et al (2022). The coordinates for all field-assessed culverts were input into ArcGIS Pro Version 3.2.1 (ESRI Inc., 2023). Consulting the orthophotography of the area (NSODB, 2019), the recorded field coordinates, and road and stream network data (NSTDB, 2023), I identified the approximate location of each culvert's inflow and outflow (Figure 3.5). Using these points' coordinates and their elevation extracted from the DEM, I used simple trigonometry and Pythagorean theorem in ArcGIS Pro's raster calculator to derive estimated culvert lengths and slopes.

$$Slope = \frac{Inflow\ Elevation - Ouflow\ Elevation}{Length\ of\ Culvert}$$

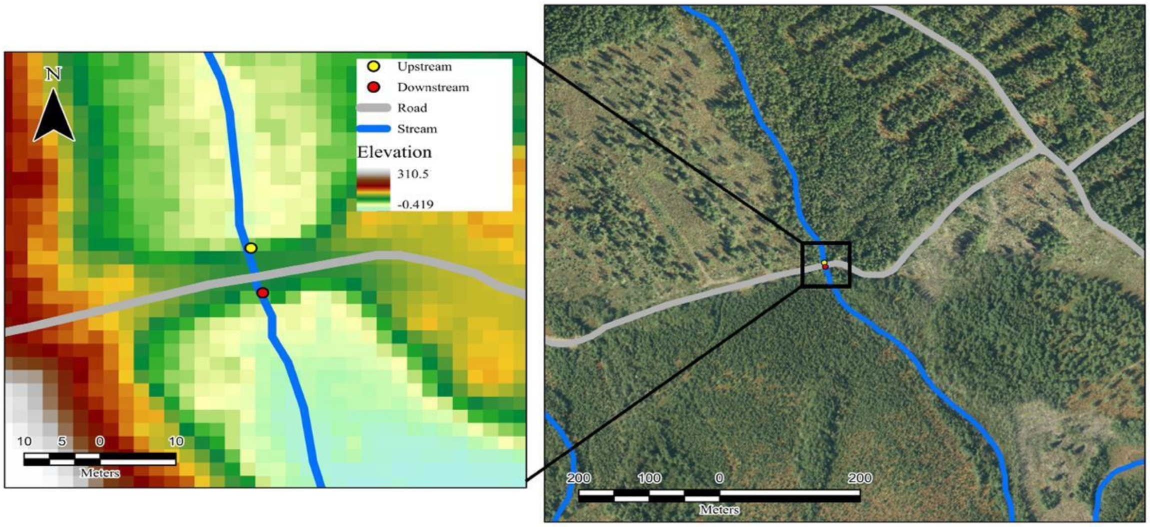


Figure 3.5 Culvert inflow and outflow identification

Slopes were estimated in the field using a clinometer with minimal success due to lack of precision in readings compared to estimated slopes. Full slope assessments using a survey rod and level were completed at 9 sites using a survey rod and level, however there were challenges accessing key points in the stream (e.g., streams no longer being wadable due to flooded upstream areas from blocked culverts) and clearly reading the survey rod due to thick vegetation that made accurate readings difficult. Assessments completed in 2009 by the SMRA identified similar challenges where slope could not be accurately or precisely measured in the field and were not included in the final report or used in any analysis (Mitchell, 2010). While there are many other landscape scale characteristics informed by spatial data that can be applied to prioritization (Kemp & O'Hanley, 2010), length of upstream habitat was simple to calculate. The lengths of linear upstream habitat was estimated by counting the distance of connected river network in the catchment area using ArcGIS Pro for each assessed culvert. Prioritization methods used by the SMRA and Anderson et al. (2022) combine passage status with a culvert's position in the stream network to determine which sites have the most habitat that can be restored. I applied the same methodology to help inform which sites should be prioritized for future restoration work by identifying culverts classified as a full or partial barrier with the largest linear distances of upstream habitat.

3.5 Statistical analysis

After all field and remote data collection done through ArcGIS Pro was completed and transcribed, I began with investigating some descriptive statistics such as breakdown of explanatory variable categories and passability categories within the sample. All numerical variables recorded were calculated and visualized within each tier of passage (passable, partial barrier, full barrier). Descriptive statistics were computed in Microsoft Excel, the statistical software R version 3.3.0, and Rstudio (Rstudio Team, 2020).

First, I tested all my continuous variables for normality using the Shapiro-Wilk test, where the null hypothesis of normality is rejected if the computed p-value is significant (Shapiro & Wilk, 1965). To validate my remotely sensed lengths, I used the Wilcoxon test to complete a pairwise comparison between estimated and field measured lengths at the 58 sites where both could be recorded. The Wilcoxon test is the non-parametric equivalent of the paired t-test and allows for comparison between means between two groups in a single sample (Wilcoxon, 1945).

The Kruskal-Wallis test was used to determine if there are statistically significant differences between each explanatory variable's categories and the ranked outcome of passability. This test is rank-based and can thus be used to compare groups based on an ordinal or continuous outcome variable (Kruskal & Wallis, 1952). The test was applied individually to each categorical variable in relation to its fish passage assessment.

I used Spearman correlations to further investigate how estimated slope, upstream distance, length, and diameter were connected to passability outcomes. Unlike the Pearson correlation, the Spearman correlation does not require linearity or normality of data and could therefore be applied to the data. The correlation coefficient. Spearman's rho is a measure of rank correlation to assess the strength and direction between ranked variables. With passability ranked where 1 = passable, 2 = partial barrier, and 3 = full barrier, a large negative rho value would indicate that large values for the explanatory variable are correlated with the culvert being passable.

Using the MASS package in Rstudio (v3.3.0; Ripley et al., 2013) I created ordinal logistic regressions using the data collected in the field and estimated remotely. The models created predict the outcome variable of passability as three ordered categories using combinations of the collected categorical and continuous variables. An ordinal logistic regression is useful as it can include analysis for partial barriers instead of a binary passable/barrier (Kemp & O'Hanley, 2010). These different models were compared using the Akaike Information Criterion (AIC), an indicator of relative model fit that is commonly used in similar studies. For example, research on brook trout's ability to pass through culverts used the AIC to compare models using explanatory variables such fish body size, time of day, and water velocity impact on passage success (Goerig et al., 2020).

For categorical data used as predictors, one level within the variable is selected as the treatment category, or baseline. Within the model, this is the category against which all other categories are compared. I selected circular and metal as the treatment levels in the regression as they were the most commonly occurring structures observed in the field (Appendix B). Informed by literature that suggests that open bottom culverts improve passability (Lehrter et al., 2024; MacDonals & Davies, 2007; Warren & Pardew, 1998) and my anecdotal experience in the field observing poorly installed box culverts, I designated circular shaped culverts to be the treatment level. Therefore, when interpreting the results of the regression, I am comparing the odds of box shaped and arch shaped culverts' ability to successfully pass salmon relative to a circular culvert. Similarly, with metal being the most common culvert material (Appendix B), I designated it as my treatment. It is important to recognize which category within a variable is the treatment because the resulting coefficients for the non-treatment categories will all be in relation to this baseline.

CHAPTER 4 – RESULTS

4.1 Fish passage assessments and culvert characteristics

Seventy-five out of 104 total culverts assessed were located in perennial streams where channel morphology, riparian habitat, water depth and discharge, bed substrate, and position within the watershed indicated that the stream was likely suitable habitat for Atlantic salmon. Culverts deemed not to be salmon habitat were often in higher reaches of the watershed where roads crossed intermittent streams, drainage ditches, very shallow wetlands, or bodies of stagnant water not connected to the St. Mary's River. Of the 75 culverts within Atlantic salmon habitat, 17 (23%) were determined to be passable and 58 (77%) were determined to be either a full or partial barrier to fish passage (Figure 4.1 & 4.2). When considered as 3 distinct categories, 44 culverts (58% of total) of were considered a full barrier and 14 (19% of total) were considered a partial barrier to fish passage.

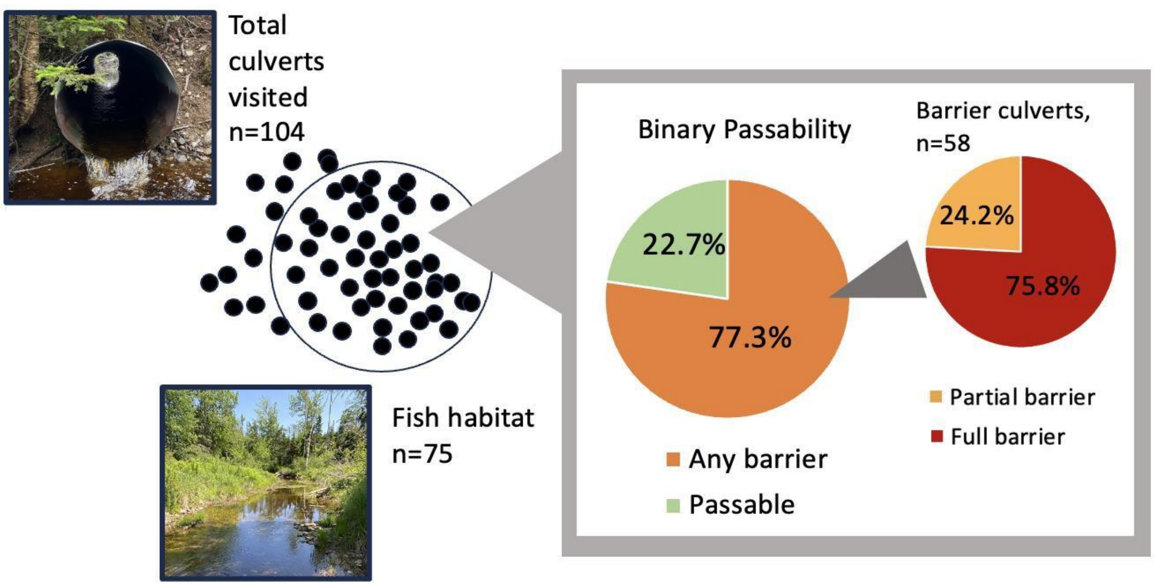


Figure 4.1 Culvert sample size and assessment results

Assessments of culvert condition for the entire sample (n = 104) showed that 38% were significantly blocked with debris; the remainder were clear. Sixty-nine percent of culverts were severely deteriorated, 17% were moderately deteriorated, and 13% had no deterioration. Many severely deteriorated culverts were crushed with bent or protruding pieces of material thus causing extreme variation in slope and debris accumulation throughout the structure (Figure 4.2). These conditions observed were often at sites where there was clear habitat fragmentation and even road wash outs.

Figure 4.2 Severely deteriorated culverts in Napu'saqnuk

The following analyses and results are limited to the 75 sites identified as Atlantic salmon habitat unless otherwise noted (i.e., subsamples where only certain measurements and observations were recorded). The most prevalent rapid assessment criteria of the four outlined by the NSSA was the culvert not being completely backwatered (69%), followed by inadequate depth (53%), difference in stream width (43%), and least seen was a visible outflow drop (21%) (Figure 4.3).

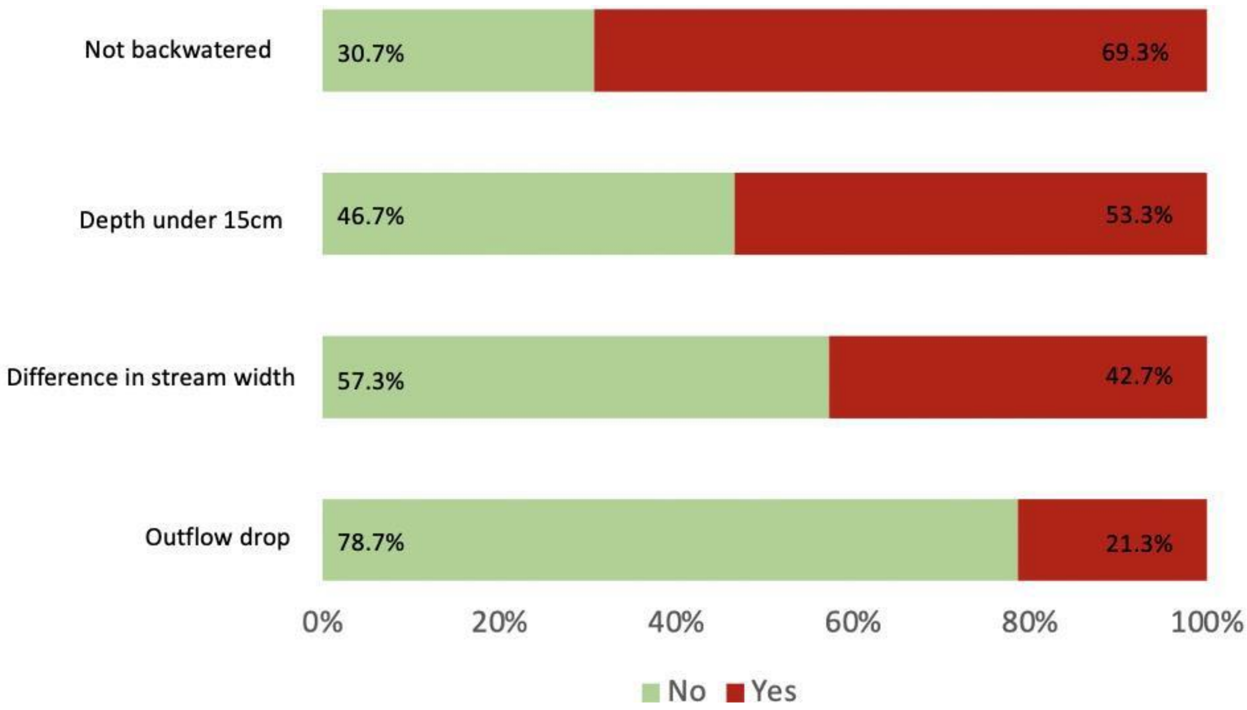


Figure 4.3 Rapid assessment results

The percentages of material, shape, entrance type and road type recorded within the sample are in Appendix A. Of note is that majority of culverts surveyed were metal and circular at 77% and 87%, respectively, with 83% located on forestry roads (n=75). The same 8% of culverts (n= 6) were wood, box shaped, and had mitered entrances.

Means and distributions of all numeric variables recorded in the field and through remote analysis are presented for each fish passage category (Table 4.1, Figure 4.4). Visual trends in Figure 4.4 identify passable culverts having higher means for road width, diameter, and amount of upstream habitat but a lower mean for estimated slope. Means for lengths in all categories were similar, however the 9 longest lengths were recorded at barrier culverts.

Table 4.1 Means for numeric explanatory variables

Variable	Passable (n=17)	Partial Barrier (n=14)	Full Barrier (n=44)
Mean diameter	1.5 m	1.1 m	0.7 m
Mean estimated length*	11.4 m	8.6 m	11.4 m
Mean estimated slope*	0.004	0.0211	0.0269
Mean upstream distance*	13.4 km	3.0 km	2.8 km
Mean recorded lengths	11.6 m	8.1 m	9.6 m
Mean recorded road width	4.9	3.7 m	2.8 m

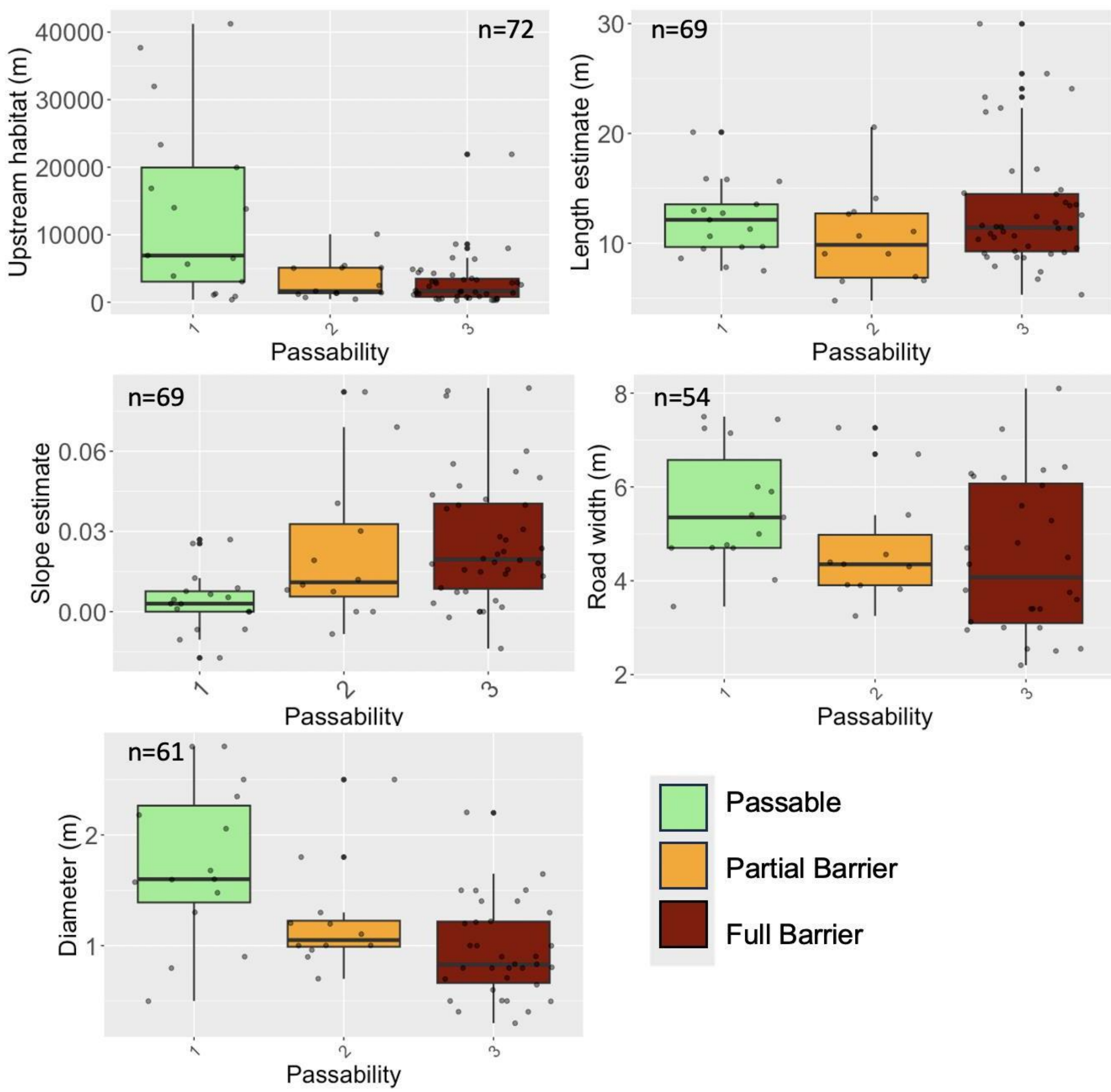


Figure 4.4 Boxplots for means by passage level

4.2 Comparing remotely estimated and field-measured culvert lengths

Only 58 culverts had data for remotely estimated and field-measured culvert lengths and were used in this comparison. Results of the Shapiro-Wilk test (Table 4.2) showed that remotely estimated and field measured culvert lengths are not normally distributed ($p<0.05$), thus rejecting the null hypothesis of normality. This data could not be further analyzed with parametric tests.

Table 4.2 Results of Shapiro-Wilk test for estimated and measured lengths

	W	P-value
Estimated culvert length	0.74	9.1 e-09*
Field measured culvert length	0.68	4.0 e-10*

* p-values significant at α =0.05

The difference in means between the two groups (remotely estimated length = 10.4 m, field measured length = 9.7 m) was further quantified through the Wilcoxon signed rank test, which indicated the null hypothesis should be rejected and that there was a significant difference between the two measurement types ($p<0.05$, n=58; Figure 4.5).

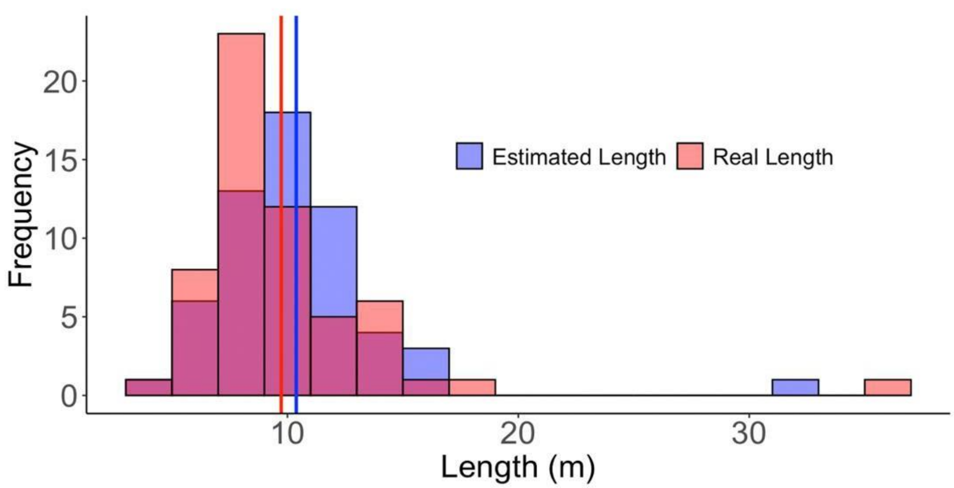


Figure 4.5 Histogram of measured and estimated culvert lengths

The Hodges-Lehmann estimator indicated the median of pairwise differences to be approximately 0.85. Although there is a significant difference between means of the groups, this test quantifies the median difference between observations to be under 1 m.

The Hodges-Lehmann estimator indicated the median of pairwise differences to be approximately 0.85. Although there is a significant difference between means of the groups, this test quantifies the median difference between observations to be under 1 m.

4.3 Local and landscape explanatory variables

Before modelling relationships to passability through regression, local and landscape explanatory variables were investigated to explore potential combinations of variables to explain fish passage response. inform which should be included and how. A Kruskal-Wallis test was used to assess whether there is a statistically significant difference in the distribution of fish "passage types" across categories of each explanatory variable (Table 4.3). A significant difference in fish passage was observed across the culvert shapes and across the road types ($p<0.05$).

Table 4.3 Results of Kruskal-Wallis test for categorical explanatory variables

Variable	H	Df	P-value
Shape	7.54	2	0.02*
Entrance type	1.07	2	0.59
Road type	4.45	2	0.02*
Material	1.77	3	0.62

* p-values significant at α =0.05

Due to varying field conditions and challenges in spatial data analysis (described further in study limitations), the sample size for each continuous variable varied. Shapiro-Wilk test results to assess normality (Table 4.4) indicated strong evidence to reject the null hypothesis of normality for several continuous explanatory variables: remotely estimated culvert slope, upstream distance, estimated culvert length, and culvert diameter. While strong evidence was lacking to reject the null hypothesis of normality for road width, the smaller sample size (n=54) may have influenced the test results.

Table 4.4 Results of Shapiro-Wilk test for all continuous explanatory variables

Variable	W	P-value	N
Estimated slope	0.90026	4.47e-05*	69
Upstream distance	0.6107	1.60e-12*	72
Estimated length	0.8836	1.05e-05*	69
Diameter	0.000604	6.04e-04*	61
Road width	0.96571	0.1242	54

* p-values significant at α =0.05

Spearman correlations between each continuous explanatory variable and passability responses indicated significant relationships ($p<0.05$) for remotely estimated culvert slope, upstream distance, and field measured culvert diameter (Table 4.5).

Table 4.5 Results of Spearman correlation for continuous explanatory variables

Variable	Rho	S	P-value
Estimated slope	0.420	31770	3.32e-04*
Upstream distance	-0.363	84753	1.74e-03*
Estimated length	0.061	51412	0.62
Diameter	-0.495	56541	5.01e-05*
Road width	0.317	34552	0.02*

* p-values significant at α =0.05

As culvert slope increased, fish passability (passable = 1, partial barrier = 2, barrier = 3) tended to decrease (Rho = 0.420). As amount of upstream habitat increased, passability increased as well (Rho = -0.363), showing sites closer to the stem of the river were more often passable.

Finally, as diameter increased, passability tended to increase as well (Rho=-0.495). Estimated culvert length and passability were not shown to be significantly correlated. Using Fisher's exact test to check independence between categorical variables provided test statistics with p-values of

<0.05 between each categorical variable (Table 4.6, n=75).

Table 4.6 Results of Fisher's test of independence

Variable	Shape	Material	Road type
Material	1.79e-07*		
Road type	0.02*	4.73e-05*	
Entrance type	1.45e-09*	7.86e-09*	1.41e-03*

*p-values significant at α =0.05

As such, the null hypothesis of independence between explanatory variables was rejected.

While Fisher's test itself does not assess multicollinearity, significant associations between categorical variables indicate the potential for multicollinearity and informed which explanatory variables were included within regression models.

4.4 Regression modelling

Four final regression models were retained from 10 tests of variable combinations to investigate what factors may be influencing the ability for Atlantic salmon to move through road culverts (Table 4.7).

Table 4.7 Regression models

Model #	AIC	Residual Deviance	Regression Equation
6	76.57	60.57	B_0 + (2.22) Box – (2.74) Arch – (3.49) Diameter + (87) Slope – (0.00026) Upstream Distance + (0.2964) Estimated Length
7	79.42	65.42	B_0 + (2.42) Box – (2.06) Arch – (4.41) Diameter + (90.94) Slope + (0.25) Estimated Length
5	81.55	73.55	B_0 – (2.32) Road width – (0.19) Diameter
1	82.56	68.55	B_0 + (2.59) Box – (2.74) Arch – (2.57) Diameter + 77.08lope) – (0.00018) Upstream Distance

The regression model with the highest amount of explanatory power to explain Atlantic salmon passability through culverts included diameter, culvert shape, remotely estimated slope, and upstream habitat distance as predictors (AIC = 76.6). This model had an AIC > 2 points lower than any other models. In this regression output (Appendix C), culvert shape and diameter were the most important predictors for passability. Culverts with a box shape had a coefficient estimate of 2.22 (SE = 5.434e-03, t-value = 4.084e+02), indicating they were associated with a higher likelihood of being a barrier compared to the set baseline of the odds of circular culvert. Conversely with a coefficient of -2.47, arch culverts had greater odds of passage than both the box and the circular shapes (SE = 1.109e-02, t-value=-2.474e+02). With a coefficient of -3.49, larger diameters were a predictor of a culvert being more likely to be passable (SE = 1.841e-02, t-value = -1.896e+02). Slope and length have smaller effects, both decreasing odds of passability as they increase. Upstream habitat distance also had a smaller coefficient value of -0.00026, indicating that increasing amount of distance upstream slightly increased odds of passability.

Using the results of this regression, culverts most likely to be assessed as passable are slightly closer to the main stem of the river, have large diameters, have estimated slopes closer to 0, and are arch-shaped.

4.5 Identifying culverts for remediation

Eight culverts for priority remediation have been identified in the West Branch of the St. Mary's River based on fish passage, estimated upstream linear habitat, and previous culvert assessment information from the SMRA (2010) (Table 4.8, Figure 4.6). Of these recommended sites, three are wooden box culverts, four are metal circular culverts, and one is an open bottom metal arch culvert (Table 4.8). All eight culverts do not have adequate backwatering and all but one site one show significant difference in stream width above and below the crossing. As outflow drops were the least common criterion seen in the field, only one of these culverts had a visible drop. Half of priority sites had issues with depth less than 15 cm at least one point within the structure.

Table 4.8 Prioritized culverts for future remediation

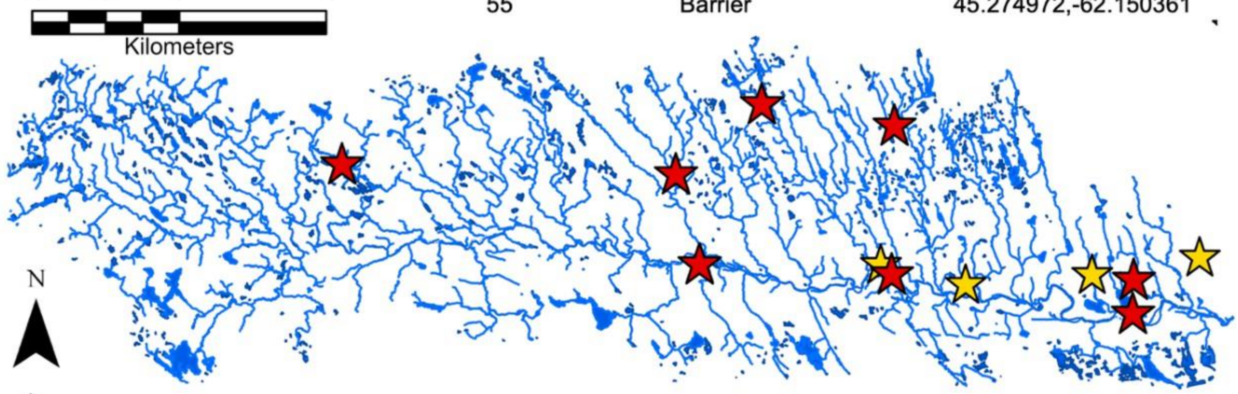
2023 ID	SMRA ID	Barrier Level	Estimated upstream habitat	Culvert Type	Rd Type	1	2	3	4
C049		Full	21.9 km	Wood, box	Highway		✓	✓	✓
C021	80	Partial	10.1 km	Wood, box	Highway	✓		✓	✓
C018		Full	8.6 km	Metal, circular	Forestry		✓	✓	✓
C084		Full	8.0 km	Metal, circular	Forestry		✓	✓	✓
C103		Full	6.6 km	Metal, circular	Forestry			✓	✓
C010		Full	6.4 km	Metal, circular	Forestry		✓	✓	✓
C066		Partial	5.4 km	Metal, Arch	Forestry			✓	✓
C072		Partial	5.1 km	Wood, box	Forestry			✓	

1. Outflow drop
2. Depth less than 15 cm
3. Not backwatered
4. Difference in stream width above and below

SMRA 2009 Prioritized (West branch only)

SMRA ID	Status as of 2023	Coordinates
80	Partial Barrier	45.279472,-62.389889
57	Barrier	45.270722,-62.227639
68	Bridge	45.279278,-62.279472
55	Barrier	45.274972,-62.150361

10 5 0 10



Prioritized Culverts

Culvert ID	Category	Passage	Coordinates
C021	Primary	Partial Barrier	45.27941,-62.39025
C018	Primary	Full Barrier	45.27512,-62.27281
C084	Tertiary	Full Barrier	45.34822,-62.35221
C049	Secondary	Full Barrier	45.3181,-62.4047
C010	Primary	Full Barrier	45.25817,-62.12549
C066	Tertiary	Partial Barrier	45.33898,-62.27116
C072	Tertiary	Partial Barrier	45.27279,-62.1249
C103	Tertiary	Full Barrier	45.32236,-62.60869

Figure 4.6 Map of prioritized sites for remediation

Of the eight sites recommended for remediation by the SMRA, only 4 are within the West Branch. SMRA site #68 at Hattie Brook was found to have been replaced by a bridge through our field assessments although it was not noted in spatial data used for field work planning or analysis. Nearly fourteen years after their original assessment, the three other sites prioritized remain either partial or full barriers (Figures 4.7-4.9). Culvert #55 at the McLeod Lake outflow was identified as having an outflow drop and depth issues (Mitchel, 2010). The same issues were identified in the 2023 assessment (Figure 4.7).

Figure 4.7 SMRA site #55

Similarly, culvert #57 was identified by the SMRA to have an outflow drop and insufficient water depth (Mitchell, 2010). The same issues were identified this past field season with no evidence of remediation work being completed (Figure 4.8).

Figure 4.8 SMRA site #57

Site #80 identified by the SMRA for remediation was assessed to remain a partial barrier after the installation of a fish ladder (Figure 4.9). Although the outflow drop is no longer a complete barrier to adult salmonids who can use the fishway, depth within the culvert itself remains a concern. In their recommendation of the fishway, the SMRA notes that success of any installed structure at this site should be monitored for success (Mitchell, 2010).

Figure 4.9 SMRA Site #80

CHAPTER 5 – DISCUSSION

5.1 The state of culverts and connectivity

As Atlantic salmon struggle to recover, it is critical that their vital habitat is highly connected to allow access to key areas for foraging, spawning, and refuge. Although my sample size of 75 is relatively small, with 77% of surveyed culverts contributing to either complete or partial fragmentation of stream habitat my results provide a glimpse into what seems to be the dire state of habitat connectivity for Atlantic salmon. Of the four culverts identified for remediation in the West Branch through the SMRA's 2009 surveys, three remain partial or full barriers to passage (Results Figures 4.7-4.9; Appendix D). Deterioration, accumulation of debris, and improper installations were observed across the watershed to have created conditions of low depths, high velocities, and perched inflows. In some cases, culverts were so deteriorated or clogged that no water was moving through the structure, thus causing flooding and creating problems for infrastructure and wildlife alike. At many sites with severe debris blockages, evidence of beaver activity was observed. While most visited sites were barriers, four sites previously identified as barriers in the NSSA database including one site prioritized by the SMRA are no longer barriers, with three having been replaced by bridges and one culvert now being passable (Appendix D).

The results of my passability assessments in Napu'saqnuk align with NSSA's estimation that 60 to 80% of culverts in the province are barriers to some or all fish species (Nova Scotia Salmon Association, 2020). This is congruent with previous studies in and outside of the province that have found upwards of half of culverts to contribute to fragmentation (Hicks & Sullivan, 2008; Langill & Zamora, 2002; Poplar-Jeffers et al., 2008). The combined 86% of culverts that were either moderately or severely deteriorated is indicative of the lack of timely replacement and monitoring occurring on both public highways (348, 347, 374) and active forestry roads on leased crown land. Neglect is further evident in the prevalence of sites with debris blockages (38%) which contribute to reduced passability and can precipitate road washouts and flooding (Figure 5.1).

Figure 5.1 Debris clogged culvert causing road washout

Outflow drops are identified to be a main source of aquatic fragmentation (Diebel et al., 2015; Januchowski-Hartley et al., 2014) and during assessments were often the first visual indicator of a site being a barrier. While presenting the most obvious challenge to fish passage it was the least recorded rapid assessment criterion with only 21% of sampled sites having a visible outflow drop (Figure 4.3).

5.2 Applications of remotely sensed characteristics

Remotely estimated culvert lengths were shown to be significantly different than those measured in the field, however, the Hodges-Lehmann estimator indicates that the median difference in paired measurements to be within 1 m. Considering that culvert lengths were estimated using a DEM with a 2 m spatial resolution, the difference between measurements is significant and should be noted but it does not invalidate the application of this information if its limitations are kept in mind. Due to safety concerns and accessibility challenges in the field, I was unable to measure culvert lengths at 32 field sites. Supplementing this dataset with remotely estimated lengths allowed for a more fulsome sample to use in further analysis (n=69).

Slope estimations calculated using the remotely estimated lengths and the DEM were limited in their application due to a lack of ground-truthed data for validation. Slope estimates from Arsenault et al (2022) were not significantly different from their estimations using this method. My estimated slope calculations did not exceed 0.08%, while remote estimates for culverts in the Restigouche watershed ranged from 0.03% to 4% (Hicks & Sullivan, 2008). The Restigouche River flows through Northern New Brunswick and sees more drastic changes in elevation (700 m) than the Napu'saqnuk (310 m), which could explain the difference in observed slopes. While the accuracy of my estimations' have not been validated, the observed trend of lower slopes estimated at passable culverts (Figure 4.4) suggests that leveraging DEM data can still help provide insight for prioritizing fieldwork efforts.

Comparisons of passability and estimated upstream linear habitat collected through desktop analysis (Figure 4.4) indicated that barrier culverts were more often further up in the watershed than near the main stem of the river. These findings are similar to Arsenault's findings where 44% of barriers were in first-order streams (Arsenault et al., 2022) and the research of others as well as others who have previously found culverts to frequently fragment connectivity in lower-order streams (Keller et al., 2011). With smaller streams, lower flows, and often situated higher up in the catchment areas, these lower order streams have higher slopes (Arsenault et al., 2022) and can be prone to undersized installation (Langill & Zamora, 2002).

Headwater streams provide essential habitat for foraging, spawning, and shelter as well as important thermal refugia in warmer temperatures (Frankiewicz et al., 2021; Wilbur et al., 2020). Therefore, increased fragmentation in these upper reaches is a serious concern. Conversely, the presence of many observed passable culverts near the mainstem maximizes the potential accessible habitat. Unlike semi aquatic or terrestrial species who have more mobility, fish move through riverine habitat linearly and are thus limited as to how they can access a landscape.

When barriers appear at the bottom of a river network, they can quickly fragment large amounts of habitat. Like the estimated length and slope, upstream linear habitat data was collected remotely with minimal validation and should be interpreted with caution but can be utilized to better contextualize barrier culverts in the stream network for management and restoration. The SMRA uses upstream habitat to inform prioritization (Mitchell, 2010), with site #80 estimated to have over 8.85 km of available habitat. Using ArcGIS Pro, I estimated this site to have 10 km of upstream habitat to reach similar conclusions for prioritization (Table 4.8). These estimations, comparisons to my own field measurements, and other's results demonstrate how information can be extracted from river network and DEM data before fieldwork to provide basic insights and assist in prioritizing further study and restoration efforts.

5.3 Characteristics impact on passability

The results of my regression analysis point towards diameter and shape having large impacts on a culvert's ability to pass fish. Increasing diameter size decreased odds of the site being a barrier. This is seen in the highest scored model (Table 4.7) and is reflected in culvert installation guidelines in which DFO recommends that culverts installed in fish bearing streams have a minimum diameter of 1 m (DFO, 2015). Of the surveyed culverts in fish habitat, 35% had a diameter under 1 m however almost all of them would have been installed years if not decades before these guidelines were put in place. Culvert diameter as a predictor of passability is a complex explanatory variable as it can be a function of stream size (larger streams = larger diameter) however, this is not always the case as many of the culverts assessed were undersized for the stream in which they were installed (Frankiewicz et al., 2021). These undersized culverts can cause excessive flow constriction and high outlet velocities, and in extreme cases flooded upstream habitat (Lehrter et al., 2024).

Of the categorical variables, shape had the greatest significant correlation with passability and the regression model with the best score included it. I did not include more than one categorical variable in each regression as I found strong evidence of dependence in both the Fisher's output (Table 4.6) and from general field observations of the same material, shape, and entrance type occurring together. With circular as the baseline category, a given culvert is more likely to be a barrier if it is box shaped and less likely to be a barrier if it is arched (Table 4.7; Appendix D). Arched or open-bottom culverts allow for the natural substrate to continue throughout the structure and does not contribute to as much constriction of the natural stream (Figure 5.2) (DFO, 2015; Lehrter et al., 2024).

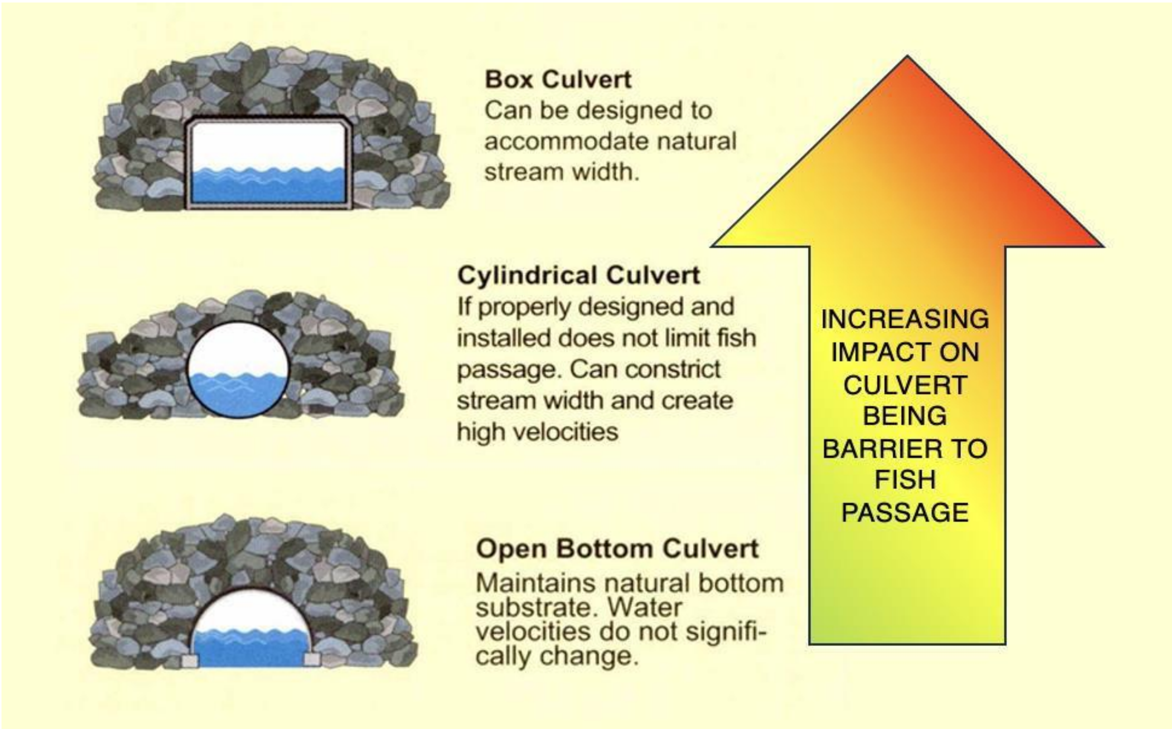


Figure 5.2 Culvert shape categories and impacts (DFO, 2015)

Both installation guidelines and previous studies have identified open-bottom culverts as an ideal stream crossing installation that allows for depth, velocity, and sediment transport to remain unchanged thus being optimal for fish passage (DFO, 2015; MacDonald & Davies, 2007; Kilgore et al., 2010; Warren & Pardew, 1998). Because of this, open bottom culverts may require less species-specific information on swimming abilities and behaviour since the culvert theoretically will not change the stream conditions (Lehrter et al., 2024). For the same reasons, a severely deteriorated culvert with an entirely rusted out bottom can support passage better than when its artificial bottom is intact. This of course is contingent on the deterioration not causing the plethora of new challenges to passability noted earlier. Although they favour passability, open bottom culverts, like circular and box culverts are vulnerable to becoming a barrier over time. This is true for all characteristics recorded – for all shapes, materials, sizes, and positions in the watershed, any culvert left unmaintained will degrade and fill with material thus becoming impassable. On decommissioned resource roads, structures were abandoned in streams where they continue to degrade and fragment habitat for years after usage ends (Figure 5.1). These incidences indicate that once logging ends, roads in Napu'saqnuk are not being decommissioned properly and are causing ongoing and unnecessary fragmentation. My field observations of these occurrences identify the need for regulatory responsibility as recommended by Langill and Zamora (2002) through their suggested culvert audits which could ensure proponents' compliance with their *Fisheries Act* habitat protection responsibilities (Langill & Zamora, 2002).

5.4 Prioritizing barriers for restoration and collaborative monitoring

Studies show that habitat fragmentation can be mended through the remediation of barriers restoring lost upstream habitat where Atlantic salmon have then recolonized hundreds of metres of upstream habitat once it was made available to them (Erkinaro et al., 2017). I have prioritized culverts by ranking barrier sites and considering additional field notes and notes from previous assessments to maximize the amount of habitat to be restored. My first-hand knowledge from a field season in Napu'saqnuk, data from other organizations, and the results of my own analysis all inform my selected priority sites for remediation. It is recognized that passability assessments for culverts vary drastically in both methodology in results (Kemp and O'Hanley, 2010; Bourne et al., 2011) and therefore may benefit from a holistic and scientific approach.

Data collection and sharing through the NSSA and SMRA has provided insight into the state of aquatic connectivity over time, allowing me to compare assessments and identify changes between previous survey efforts and my own last summer. My research has greatly benefitted from information sharing between local organizations, industry, and academia but future research could be further supported with more robust connections and attention to communicating findings between groups. This experience emphasizes importance of central and well managed geospatial databases to promote the continuity and accessibility of structural and environmental data to facilitate conservation (Kemp and O'Hanley, 2010).

While information on previous assessments provides important historical information, inconsistencies in data provided between the NSSA's Aquatic Connectivity Analytical Database and the information from SMRA's 2009 survey. Specifically of note are three sites identified for remediation by the SMRA (Mitchell, 2010) are labelled "passable" by the NSSA. I identified these sites to be either partial or full barriers and through a comparison with photos taken by the SMRA in 2009, it seems that they have been a barrier since that time. Discrepancies in available records create a barrier to efficient remediation. The

Canadian Wildlife Federation’s Canadian Aquatic Barrier Database (CABD)(Canadian Wildlife Federation, 2024) could be used as a repository where data collected across local non-governmental organizations, government, and industry can be synthesized and accessible to the public. Although the CABD is currently limited to waterfalls, dams, and fishways, this database is an excellent platform that could provide a full picture of aquatic connectivity in the future. As a multi-year project receiving both public and private funding, the CABD has the potential to play a key role in data management that can inform aquatic connectivity Nation-wide.

Connected networks for information synthesis and exchange can facilitate collaboration on aquatic connectivity restoration, however, even when barriers are clearly identified and communicated, they can remain in the network un-remediated year after year as is the case with sites identified in 2009 and revisited in 2023 (Figures 4.7-4.9). With over three quarters of sites assessed as barriers to connectivity there remains few monitoring requirements or frameworks for accountability surrounding the installation and upkeep of both government and private infrastructure projects in the area. Atlantic salmon in Napu’aqnuk will continue to suffer from a fragmented freshwater habitat if this remains to be the case.

5.5 Limitations

The processes of culvert field assessments and remote analysis are admittedly subjective (Kemp and O’Hanley, 2010), and the resulting conclusions can vary drastically (Bourne et al., 2011). The rapid assessment criteria developed by the NSSA that I used in the field identifies 15 cm depth as a threshold, while other organizations, such as the SMRA, use 20 cm (Appendix A; Mitchell, 2010). The reality of passage itself can be affected by other life cycle and environmental factors like fish body size, an individual’s health and motivation, the presence of predators, and temperature (Cahoon et al., 2007).

Finally, persistent barriers to fish passage I observed throughout the field assessments were debris blockages and severe deterioration. Without data on installation dates and maintenance, it is impossible to predict the state of blockages and deterioration, meaning this must be assessed in person and culverts clogged with branches and leaf litter can quickly become passable again post debris removal. As seen with this example of debris blockages, passability is not truly discrete and can change over time. Although I considered reclassifying passability outcomes as a binary (passable/barrier) to inform a logistic regression instead of an ordinal regression, in the field there was a clear group of sites where "partial barrier" was the assessment most reflective of reality and the three categorical outcomes fitting the data best. A prioritized site by the SMRA had a fish ladder installed (Figure 4.9); while passability was improved since the site's last assessment in 2009, it was by no means 100% passable for all fish resembling the model organism, and an excellent example of the need for this middle category to adequately represent conditions seen in the field. Given the known complexity of passability and the varying conditions I observed in the field, my findings must be contextualized with the many factors at play in aquatic habitat connectivity.

Nova Scotia saw extreme weather throughout the entirety of 2023, notably a warm and dry May followed by the most devastating wildfire season on record (Snoddon, 2023). From June 1st to August 31st, the watershed received approximately 600 to 800 mm of rain (Snoddon, 2023). Extreme weather events caused large fluctuations in stream depth and velocity between field work trips and injected more uncertainty into already subjective culvert assessments. When assessing a culvert's functionality, it is important to consider if the flows observed in that moment are representative alongside consideration of regular seasonal variation. While this was kept in mind throughout assessments done throughout June and July, this study cannot quantitively account for this uncertainty. In future assessments, this limitation can be addressed by determining specific minimum base flows and in-culvert depths that reflect the average riffle depth upstream of the structure (Mitchell, 2010).

Due to challenges in the field, validating slopes of culverts remotely estimated was not feasible. With significant wind blow down causing dense vegetation cover around inflow and outflow, often simply locating the culvert itself was challenging led alone completing an accurate assessment. For the same reasons, identifying inflow and outflows with precision and accuracy via DEM and orthophotography was difficult and sometimes impossible thus contributing to incomplete data. While there is a slight trend in the estimated slopes in relation to passability, the range of measured slopes is small and has little meaningful application without ground-truthed measurements to compare to this data. With culvert lengths having very little impact on passability and slope estimates not having been validated, the most important information determined remotely is the amount of upstream habitat that is either available or unavailable to Atlantic salmon, based on the culvert's assessment. This analysis identified that elevation could potentially inform slope and be used to streamline field assessments which is concurrent with previous work (Arsenault et al., 2022; Januchowski-Hartely et al., 2014), however it is by no means a conclusive framework for remote assessment and prioritization. Rather, my results indicate that spatial data collected remotely like elevation change and upstream habitat lengths should be used in combination with knowledge from previous assessments to inform further assessments, installations, and remediation. SMRA prioritizes culverts with the largest network upstream (Mitchell, 2010) thus ensuring that remediation efforts restore maximal habitat.

While my results provide a better idea of how culvert characteristics can be applied to predict passage, lack of comprehensive and up to date records on stream culvert installations - on both public highways and resource roads leased to industry - limits its application for predicting fish passability. The relative ubiquity of deterioration and debris blockages in the sample suggest that date of installation would be an excellent explanatory variable to include in future predictive models as they are both functions of time. Unfortunately, this information was not available. I have identified that closed bottom culverts in areas with greater elevation changes with small diameters, especially relative to stream size, are most likely to be fragmenting aquatic connectivity in Napu'saqnuk. To apply this information more broadly to the watershed, knowing where culverts are and what they are made of is required; this data could then be supplemented by remote estimations of length, slope, and upstream habitat. Publicly accessibly culvert-by- culvert installation and maintenance record keeping has not been a priority for governments or industry to-date in Nova Scotia. As such, freshwater connectivity improvement projects may largely rely on community-based culvert monitoring data from volunteers (e.g., SMRA), researchers, or other groups sponsored by non-governmental organizations like the NSSA (*NSSA Adopt A Stream*, 2020).

5.6 Directions for future study

A future study of Napu'saqnuk that implements Arsenault's full methodology has the potential to provide a landscape scale analysis that can identify culverts likely to be causing a barrier to fish passage. This would require a high precision slope measurement tool to ground truth remote analysis, such as the Zip Level (Arsenault et al., 2022) and the highest spatial resolution DEM available for the area. Additionally, more information on stream network structure and trends in passability can be investigated through the incorporation of stream order into this analysis. The Dendritic Connectivity Index (DCI) (Cote et al., 2009) can inform how culverts impact the structural and functional connectivity of a river network when informed by barrier assessments and biological data (Bourne et al., 2011). In the future, analysis including DCI can inform further study and management considerations for the St Mary's River. This can be facilitated using plug-ins for existing geospatial software, like the Fish Passage Extension (FIPEX) v10.4 for ArgGIS Pro to calculate DCI thus allowing for a better understanding of the cumulative effects barriers have on longitudinal connectivity (Oldford et al., 2023).

Additional spatial analysis with my collected data can be applied to restoration and management, such as the density of barriers within tributary catchments, or most efficient routes to maximize the number of culverts that can be accessed in each field trip. While stream crossing density analysis exists at the watershed level for NS (DFO, 2020) there is no current analysis for within Napu'saqnuk. Another future consideration when prioritizing culverts for field assessments could be areas with known beaver populations or recent beaver activity. With debris being a cause of fragmentation and many debris blocked sites showing evidence of beavers, applying knowledge of where beavers are likely to be found in relation to culvert locations could help pinpoint blockages. Additional water quality metrics can be collected at each site, like temperature, salinity, turbidity, conductivity, and dissolved oxygen (Ho et al., 2020) along with a full assessment of riparian zone (Collison & Gromack, 2022) to better understand how other environmental factors could be impacting salmon in their freshwater habitat. To further refine prioritization, more information on which streams salmon return to can be determined through further ecological monitoring using techniques like acoustic telemetry and mark recapture to better understand the distribution of salmon in the river to further identify areas for prioritized restoration.

Similar studies should be done to determine efficacy of installed fishways like at SMRA site #80, as suggested (Mitchell, 2010), especially since such sites are still assessed to be a partial barrier. A detailed prioritization should consider cost of prescribed undertakings to identify sites where minimal costs can restore maximal upstream habitat. To further optimize the cost-benefit of restoration efforts, considerations of other species of conservation interest in the area can be incorporated into both passage assessments and remediation designs. With existing information on habitat requirements, distribution in the river, swimming abilities, and life cycle, species like the American eel can enjoy improved habitat connectivity along with the Atlantic salmon. More information on the state of the Atlantic salmon in Napu'saqnuk and Southern Uplands DU is expected to be available as of November 2024 with the publishing of the COSEWIC status report (COSEWIC, 2024). The findings of this report may help inform the direction of future investigations into habitat connectivity in the watershed.

CHAPTER 6 – CONCLUSION

My findings contribute to the growing body of knowledge on how individual characteristics of culverts and their position on the landscape can effectively predict their ability to pass fish. Of the local characteristics examined, diameter and shape are the best predictors of passability where larger diameters and arch shaped culverts see increased odds of fish passage. These findings also point towards smaller diameter closed bottom culverts to be indicators that a site may be a barrier. Using the results of culvert assessments completed on site in combination with information on length of habitat upstream from known barriers I have identified 8 current barriers to connectivity that should be prioritized for remediation. A comparison of sites I assessed to be a barrier with a previous assessment report done in 2009 reveals that some culverts have been barriers for at least 15 years. While remediation projects were observed to have been undertaken at some sites, it is unclear if these efforts have been fruitful in creating functional connectivity for the Atlantic salmon of Napu'saqnuk to spawn, forage, and shelter.

To optimize assessment and restoration efforts in the future, it is essential that government and industry diligently record data on road building and maintenance wherever these activities coincide with salmon habitat. These records should be updated systematically, and maintenance of stream crossing infrastructure should be scheduled regularly. Compliance of new installations with existing guidelines should be verified both on Crown land leases and public highways. Finally, when barriers are identified, it is imperative that passage is restored in a timely manner to limit the ecological impacts of fragmentation. This requires support for local organizations performing restoration and remediation through sustained funding and collaboration between relevant private and public entities like the proponents of industry projects, DFO, the provincial department of Public Works (previously Transportation and Infrastructure Renewal).

If decision makers are committed to protecting the remaining wild Atlantic salmon of Napu'saqnuk, it is time to commit to continued dedicated funding for monitoring and restoration of in-stream crossings in key habitat. If this salmon population is eventually listed under SARA, additional funding should be provided for culvert barrier removal and restoration through the Habitat Stewardship Program for Species at Risk (Government of Canada, 2024). As the negative effects of barriers on Atlantic salmon are pervasive in this watershed, a ‘restoration plan’ as part of a potential future ESA designation (DFO, 2023) should include legacy culverts as a priority threat requiring urgent attention. Enhanced proactive management measures could include a requirement for open-bottom culverts or bridges when encountering streams deemed to be within Atlantic salmon habitat during new road building. Evidence-informed policy and continued collaboration with local conservation groups presents an opportunity to reverse current habitat fragmentation and limit impacts of road building on Atlantic salmon in the Napu’saqnuk and surrounding Maritime rivers moving forward. I hope that the applications of my research can change in this key river for the better by contributing to a future where the Atlantic salmon population is recovering and its habitat connectivity is restored.

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APPENDIX A

Aquatic Connectivity Program Crossing Assessment

Site Information					
Crossing ID		Watershed Group Name			
Crossing Type	☐Culvert ☐Bridge* ☐Dam ☐Ford ☐Other	# of Culverts			
Field Crew		Date (dd/mm/yyyy)			
Stream Name		Time			
Road Name		Projection	☐ WGS84 ☐ NAD 83		
Ownership of Crossing	☐ Public Road ROW ☐ Rail Bed ROW ☐Private	Lat (deg, min, sec)			
Debris Blockage Present	☐Yes ☐No	Long (deg, min, sec)			
Description of Debris		Fish Habitat**	☐Yes ☐No		

*If crossing is a bridge or other open bottomed structure, complete bridge section
**If crossing is identified as being on a fish bearing stream, then proceed with further data collection

Photo Files			
Upstream	File Name	**Downstream**	File Name
Toward Inflow		Toward Outflow	
Through Culvert		Through Culvert	
Looking Upstream		Looking Downstream	
Other		Other	

Bridge Dimensions			
Span (m)		Wetted Width Under Bridge (m)	
Rise (m)		Average Water Depth Under Bridge (m)	
Bridge Width (m)		Stream Width Ratio	

Raoid Assessment	
There is a visible outflow drop.	☐True ☐False
Water depth is less than 15cm in at least one location inside the culvert.	☐True ☐False
The culvert is not fully backwatered.	☐True ☐False
The stream width noticeably different above and below the culvert?	☐True ☐False

If the response to any of these questions is TRUE then continue with the full assessment.

Stream Characteristics

Water Quality

Air Temp (̊C)		pH		DO(mg/L)	
Water Temp (̊C)		conductivity (µS/cm)		TDS (mg/L)	

Substrate Sizes (taken upstream of culvert in percent composition)

Fines (<0.2cm)		Cobble (6.4-25.6cm)		Bedrock	
Gravel (0.2-6.4cm)		Boulder (>25.6cm)			

Channel Measurements (taken upstream)

	Pool	Riffle	Run	Average
Wetted Width (m)				
Bankfull Width (m)				
Stream Width Ratio				

Culvert Information					
Culvert Material	☐ Concrete ☐ Corrugated Metal Pipe (Spiral) ☐ Corrugated Metal Pipe (Annular) ☐ Corrugated Plastic ☐ Wood ☐ Other	Culvert Shape	☐ Circular ☐ Box ☐ Pipe Arch ☐ Open Arch ☐ Other	Entrance Type	☐ Projecting ☐ Headwall ☐ Mitered ☐ Wingwall ☐ Other
		Is Culvert Deformed?	☐ Yes ☐ No	Deterioration	☐None ☐Moderate ☐Severe
				Baffles	☐ Present ☐ Absent
Culvert Bottom	D Closed D Open If Open, Dominant Substrate:	Variable Slope in Culvert	☐ Yes ☐ No		

Page 1 of_

Culvert Dimensions					
Culvert Measurements (m)	WIDTH	HEIGHT	Corrugation (cm)	**WIDTH**	**HEIGHT**

Additional Information			
Inflow Habitat Type	☐ Pool ☐ Riffle ☐ Run ☐ Drop	Beaver Dam Present	☐ Yes ☐ No
Backwatered	☐ 0% ☐ 25% ☐ 50% ☐ 75% ☐ 100%	Fish Observed	☐ Upstream ☐ Downstream
Embedment	☐ Embedded from Upstream D No Embedment ☐ Embedded from Downstream ☐ Fullv Embedded	X-Sectional Degree of Embedment	☐ 0% ☐ <20% ☐ >20%
Length of Culvert with Embedment	☐ 0% ☐ 25% ☐ 50% ☐ 75% ☐ 100%		

Upstream of Culvert

Elevations				**Measurements**		
	HI (m) (10 + change in tripod height)	FS(m) (survey rod reading)	Elevation (m) (HI-FS)	Water Depth at Inflow (cm)		Velocity (m/s)
				Stagnation Depth at Inflow (cm)		
Crest of Riffle Upstream				Upstream Riffle to Inflow Invert (m)		
Inflow				Culvert Length (m)		
Upstream Channel Slope(%)						

Downstream of Culvert

Elevations				**Measurements**		
	HI (m) (10 + change in tripod height)	FS(m) (survey rod reading)	Elevation (m) (HI-FS)	Water Depth at Outflow (cm)		Velocity (m/s)
				Stagnation Depth at Outflow (cm)		
				Plunge Pool Bankfull Width (m)		
Outflow						
Plunge Pool Bottom				Outflow to Tailwater Control (m)		
TailwaterControl				Tailwater Control to 2nd Riffle Downstream (m)		
Crest of 2nd Riffle				Culvert Slope		
Pool Surface Elevation				Outflow Drop (cm)		
Downstream Channel Slope						

Tailwater Cross Section

Widths	**Elevations**				**Measurements**
	Station	**HI(m)** (10 + change in tripod height)	FS(m) (survey rod reading)	Elevation (m) (HI-FS)	Water Depth (m)
Wetted Width (m)	1 (Left Bankfull)				
	2 (1/5 Bankfull Width)				
Bankfull Width (m)	3 (1/5 Bankfull Width)				
	4 (1/5 Bankfull Width)				
Bankfull Width/ 5	5 (1/5 Bankfull Width)				
	6 (Right Bankfull)				

<table>
<tr><th colspan="7">Baffle Information (Complete if culvert is baffled)</th></tr>
<tr><td>Baffle Height (cm)</td><td></td><td colspan="2">Baffle Material</td><td colspan="3">D Concrete D Metal D Wood D Other</td></tr>
<tr><td>Notch Depth (cm)</td><td></td><td colspan="2">Baffle Type</td><td colspan="3">D Straight D Diagonal
D Right Angled D Other</td></tr>
<tr><td>Notch Width (cm)</td><td></td><td colspan="2">Notch Chutes</td><td colspan="3">D Yes ☐No</td></tr>
<tr><td>Number of Baffles</td><td></td><td colspan="2">Notch Chute Material</td><td colspan="3">D Concrete D Metal
D Wood D Other</td></tr>
<tr><td>Distance Between Baffles (m)</td><td></td><td rowspan="2">Elevations</td><td rowspan="2">HI(m)
(10 + change in tripod height)</td><td rowspan="2">FS(m)
(survey rod reading)</td><td rowspan="2" colspan="2">Elevation (m)
(HI-FS)</td></tr>
<tr><td rowspan="3">Distance from Bottom Baffle to Outflow (m)</td><td rowspan="3"></td></tr>
<tr><td>Most D/S Baffle</td><td></td><td></td><td colspan="2"></td></tr>
<tr><td>Adjacent U/5 Baffle</td><td></td><td></td><td colspan="2"></td></tr>
<tr><td>Drop Between Baffles (m)</td><td colspan="6"></td></tr>
</table>

Notes

Sketch

APPENDIX B

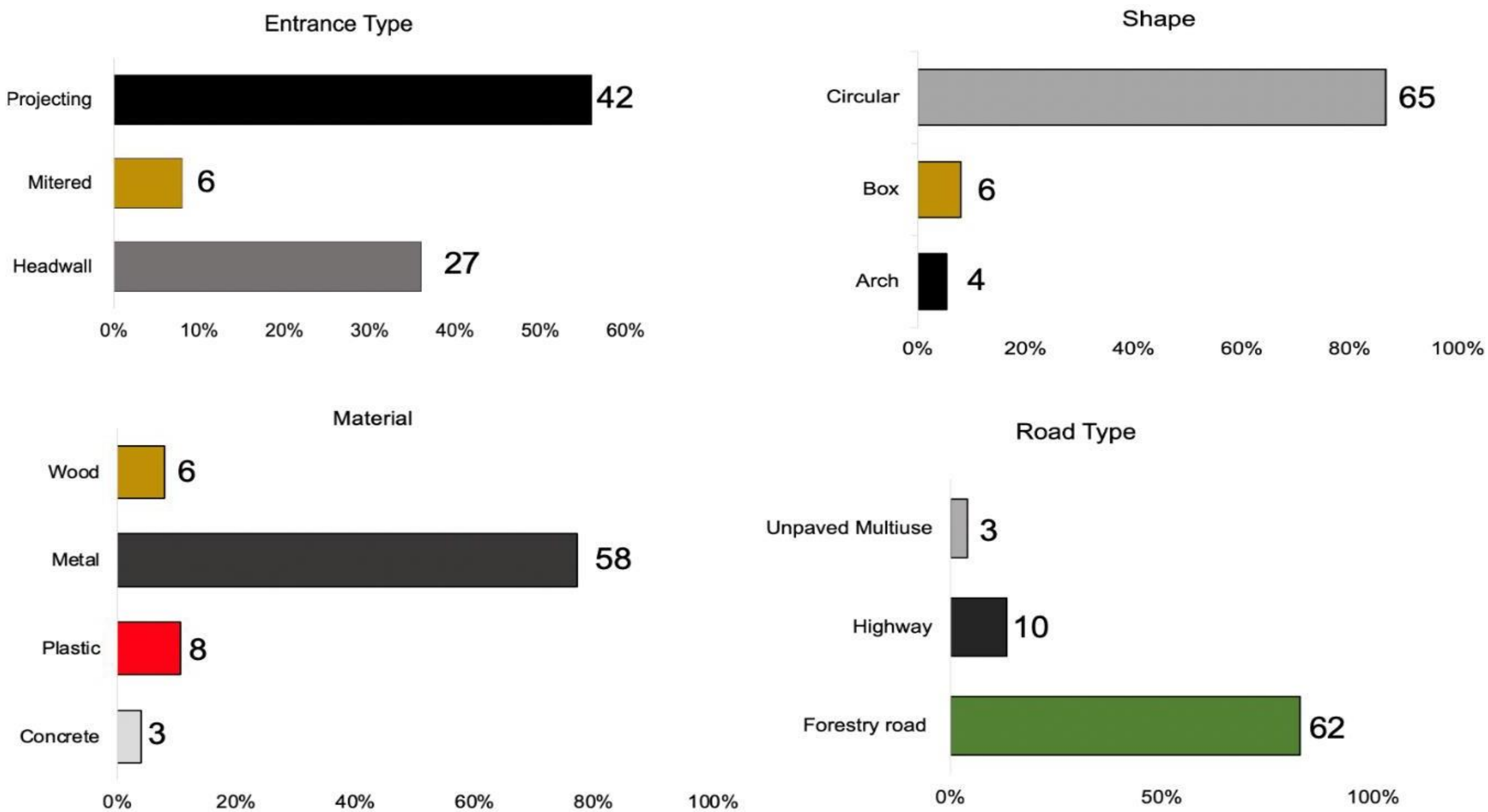

Figure B.1 Bar graphs of categorical characteristics recorded at culverts in fish habitat

APPENDIX C

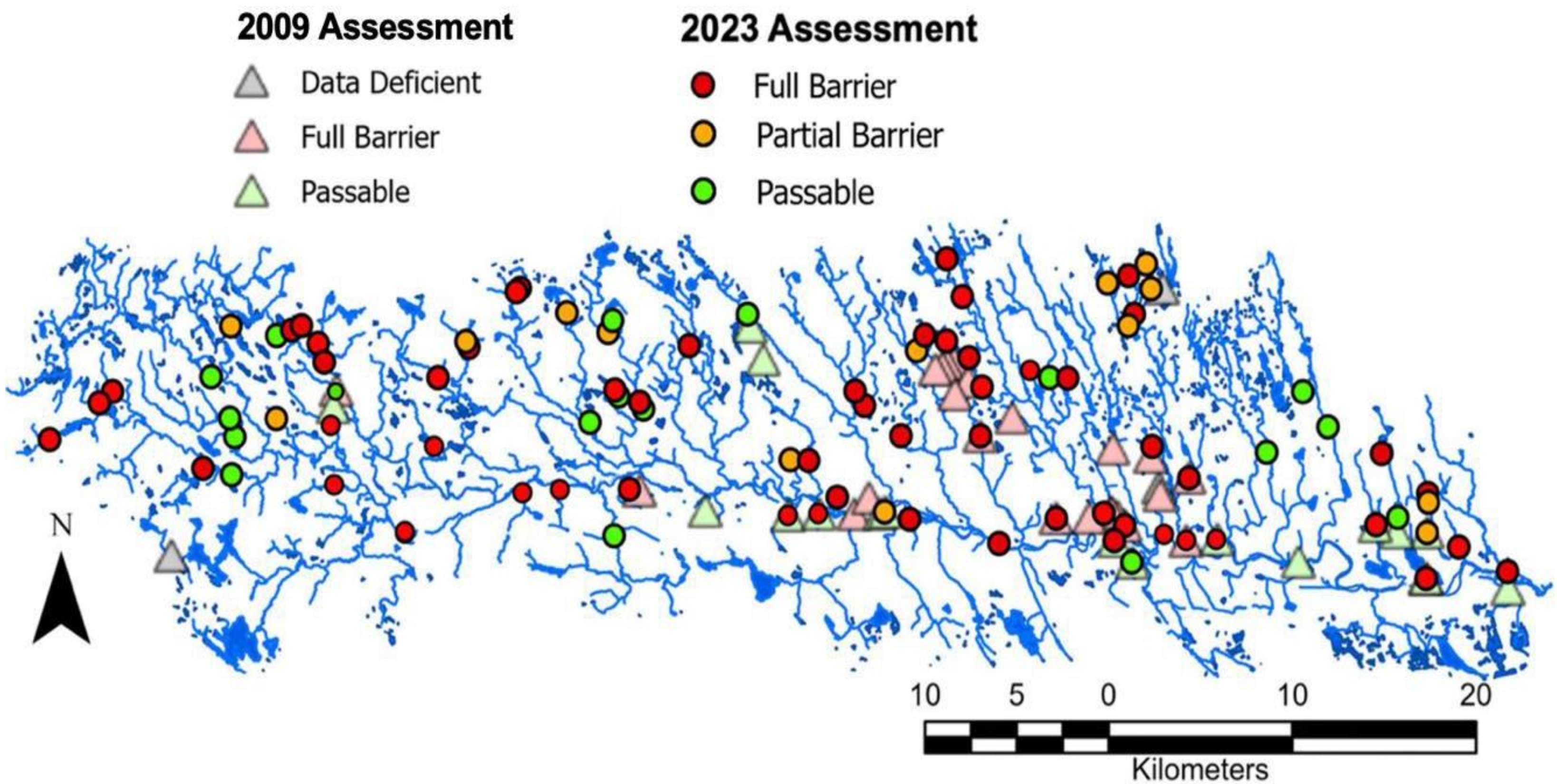

Figure C.1 Map of the West Branch of all sites assessed in 2009 and 2023 surveys

APPENDIX D

Table D.1 Regression #6

Variable	Value	Std Error	T value
Shape – Box	2.22	5.434e-03	4.084e+02
Shape – Arch	-2.74	1.109e-02	-2.474e+02
Diameter	-3.49	1.841e-02	-1.896e+02
Slope estimate	87.00	6.893e-05	1.262e+06
Upstream distance	-0.00026	1.096e-04	-2.385e+00
Estimated length	0.2964	5.615e-02	5.280e+00

Residual Deviance: 60.57

AIC: 76.57

Table D.2 Regression #7

Variable	Value	Std Error	T value
Shape – Box	2.42	1.7779	1.364
Shape – Arch	-2.06	1.9101	-1.079
Diameter	-4.41	1.1718	-3.763
Slope estimate	90.94	26.7036	3.405
Estimated length	0.25	0.1191	2.116

Residual Deviance: 65.42

AIC: 79.42

Table D.3 Regression #5

Variable	Value	Std Error	T value
Road width	-2.32	0.7000	-3.3096
Diameter	-0.19	-0.1934	-0.7854

Residual Deviance: 73.55

AIC: 81.55

Table D.4 Regression #1

Variable	Value	Std Error	T value
Shape – Box	2.59	0.0046	556.747
Shape – Arch	-2.74	0.0452	-60.644
Diameter	-2.57	0.2907	-8.850
Slope estimate	77.08	0.0038	20484
Upstream distance	-0.00018	0.0011	-1.624

Residual Deviance: 68.55

AIC: 82.56

APPENDIX E

Table E.1 Sites with change in infrastructure since last recorded assessment

Culvert ID	2009	2023	Coordinates	Road	Stream	Notes
NA*	Barrier	Bridge	(45.27928, -62.27028)	North Side West River / Barren Brook	Hattie Brook	
NA	Barrier	Bridge	(45.27781, -62.28833)	North Side West River Rd / Barren Brook	Hattie Brook	
NA	Barrier	Bridge	(45.29972, -62.27869)	Sutherland Brook	Sutherland Brook	
C005	Barrier	Passable	(45.31794, -62.65877)	Highway 374	Castley Brook	
C072	Passable	Partial Barrier	(45.27279, -62.1249)	Highway 348		Debris, Deterioration
C022	Passable	Full Barrier	(45.27892, -62.42279)	Cameron Settlement		Debris, Deterioration
C009	Passable	Full Barrier	(45.27832, -62.43761)	Cameron Settlement		Debris, Deterioration
C012**		Full Barrier	(45.27531, -62.14996)	Highway 348	MacLeod Lake	
C013**		Full Barrier	(45.27064, -62.22811)	Highway 348	Tributary of Indian Man Pool	
C021**		Partial Barrier	(45.27941, -62.39025)	Highway 348	McQuarries Brook	Fish ladder installed post 2009

*Identified for priority remediation by the SMRA (Mitchel, 2010) and as barrier in digitized layer

**Identified for priority remediation by the SMRA (Mitchell, 2010) but passable in digitized layer