A NEW METHOD FOR PRIORITIZING CATCHMENTS FOR TERRESTRIAL LIMING IN NOVA SCOTIA

ENVS 4902 Environmental Science Undergraduate Honours Thesis

Thesis by: Marley Geddes – B00609284
Dalhousie Undergraduate Environmental Science Honors Student (2012), Halifax, NS

With support of:

Supervisor: Dr. Shannon Sterling,
Assistant Professor of Earth Science and Environmental Science
Principal Investigator of Dalhousie's Hydrologic Systems Research Group

Course Coordinator: Dr. Tarah Wright,
Associate Professor of Environmental Science
Dalhousie University, Halifax, NS

Contents

Abstract

Freshwater acidification is a chronic issue in South Western Nova Scotia (SWNS). Despite reductions in emissions causing acid deposition in SWNS, water quality in the region is not predicted to improve for another 60 years (Clair et al., 2004). Acidification is the primary factor limiting the Southern Upland (SU) Atlantic salmon (*Salmo salar*) designatable unit which was evaluated as endangered by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) in 2010. The SU salmon have declined from 88-99% since the 1980's and have a high probability of extirpation in the next 50 years if habitat quality is not improved (DFO, 2013).

Liming, the addition of base cations to an acidified system, is the only mitigation method for acidification. Terrestrial liming is the addition of buffering material to the catchment of an acidified river and is a promising mitigation method for rivers in SWNS as it is sustainable and requires no maintenance (Olem, 1991). The effectiveness of terrestrial liming varies by location therefore an assessment of potential liming catchments is necessary to identify the top priority sites for terrestrial liming. The federal government and community groups are interested in terrestrial liming in SWNS to improve water quality and help support the SU salmon population but unfortunately a method for identifying and prioritizing catchments for terrestrial liming does not exist. I have developed a comprehensive and quantitative GIS decision model to prioritize catchments for terrestrial liming in Nova Scotia. The model identifies catchments that best support effective liming and the SU population; these catchments are the primary units of SU conservation when using terrestrial liming mitigation methods. Additionally this research identifies key information needs required for improved terrestrial liming catchment selection.

1. Introduction

1.1. Rationale

South Western Nova Scotia (SWNS) has some of the most acidified waters in North America (Stoddard et al., 1999). Acidification in eastern Canada is most commonly caused by acid precipitation with high levels of sulphate (SO_4^{-2}) transported on prevailing winds from central North America in combination with low Acid Neutralizing Capacity (ANC) of the regional bedrock and soils (Clair et al, 2007). ANC is the ability of the bedrock or soils to offset or neutralize acidic inputs. The 1990 amendments to the United States Clean Air Act address the issue of acidification through reductions in sulfur emissions across North America (EPA, 2013). The United States and Canada have reduced their sulfur emissions by 76% and 36%, respectively, since 1990 (EPA, 2014; Conference Board of Canada, 2014). Despite emission reductions across North America and the resulting decrease in acid precipitation in SWNS (Environment Canada, 2012), pH in the area’s freshwaters has not increased (Stoddard et al, 1999).

The chronic freshwater acidification in SWNS is a major limiting factor for the Southern Upland (SU) Atlantic salmon (*Salmo salar*) designatable unit which was evaluated as endangered by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) in 2010 (DFO, 2013). The SU salmon freshwater range includes some of the extremely acidified rivers in SWNS (DFO, 2013). The SU population has declined from 88% to 99% since the 1980s and population viability modelling for the LaHave River, an indicator river for the SU salmon, indicates an 87% probability of extirpation in the next 50 years if habitat quality is not improved (DFO, 2013).

Mitigative measures are required for the SU salmon population to avoid extirpation. Without human intervention water quality improvements are not predicted to occur naturally for another 60 years (Clair et al., 2004) during which time the SU population is predicted to be extirpated. Mitigative methods need to be implemented in SWNS streams to neutralize acidification, increase pH and improve water quality for the SU salmon. Liming, the addition of base cations to an acidified system, is the only in situ mitigation method against acidification. There are two types of liming: in-stream liming, the addition of base cations directly to the water, and terrestrial liming, the addition of base cations to the soils of an acidified catchment. Although in-stream liming is effective at improving water quality and increasing pH, it typically involves expensive machinery (i.e., lime doser) and improvements are immediately lost when liming is stopped. The advantages of terrestrial liming compared to in-stream liming is that it is less expensive, not requiring heavy machinery or maintenance, and the improvements are longer lasting (Hindar et al, 2003; Howells et al., 1995; Traaen et al, 1997; Jenkins et al, 1991). This research will provide an extensive assessment of potential terrestrial liming sites within SWNS for the conservation of the SU Atlantic salmon.

1.2. Background

Freshwater acidification was first studied in the late 1970's in Eastern Canada and Scandinavia (Clair and Hindar, 2005), and has since been recognized internationally as a serious environmental threat (Environment Canada, 2012; Clair et al, 2005; Clair et al, 2007). Surface waters that are considered acidic contain more negatively charged acid anions than positively charged base cations and thus are characterized by low pH conditions. Acidification is commonly caused by acid precipitation in conjunction with low ANC. Areas with high ANC are characterized with alkaline-rich soils formed from bedrock rich in base cations. In soils with high ANC or buffering capacity ion exchange will occur with carbonates leading to the release of base cations such as calcium (Ca^{2+}) and magnesium (Mg^{2+}) into surface waters. In soils with low pH, ionic aluminum (Al_i) will be released from aluminosilicate minerals into the surface waters (Clair and Hindar, 2005).

The primary factors contributing to acid precipitation is the burning of fossil fuels and metal refining, producing sulfur dioxide (SO_2) and nitrogen oxide (NO_2) (Environment Canada, 2012; Clair et al, 2005). Emissions from the more industrialized regions in central North America are transported east on prevailing winds where they are deposited as acid deposition in the Maritimes. Chronic acid precipitation falling in regions underlain with poor weathering bedrock with low ANC results in the acidification of the soil and surface waters. For example the granite and shale rocks underlying the majority of Nova Scotia have little buffering capacity, making the province particularly vulnerable to acidification (Clair et al, 2007).

Acidification is detrimental to freshwater ecosystems. Low pH conditions and the associated bioavailability of Al_i decreases the fitness of freshwater biota (Cronan and Schofield, 1979; Dennis and Clair, 2012). Acidification is a limiting factor for many acid intolerant species, especially fish in freshwater systems (Lacroix and Townsend, 1987; Dennis and Clair, 2012; Kure et al, 2013). Low pH and aluminum toxicity are the two underlying agents associated with acidification that are most detrimental to fish. Al_i, when not bond to organic matter in an organic aluminum complex, can attach to fish gills causing access mucus that can lead to serious respiratory issues and death (Driscoll et al, 1980; Bache, 1986; Dennis et al, 2012). Fish are most sensitive to acidic conditions at young life stages. Research has shown that the hatching of Atlantic salmon eggs were delayed or prevented when exposed to water with a pH of 4.0 to 5.5 compared to proper hatching at pH levels of 6.6 to 6.8 (Peterson et al, 1980).

SWNS has some of the most acidified waters in North America, next to point sources of sulphate pollution such as Sudbury, Ontario (Clair et al, 2007). The persistent and severe acidification in SWNS is due to a combination between the acid deposition caused by SO_2 emissions from central North America, the low ANC of the local bedrock and the resulting alkaline-poor soils in Nova Scotia (Clair et al, 2007; Fox et al, 1997; Sterling et al., 2014-a). Despite the low pH conditions that enable the ionic form of aluminum (Al_i), aluminum toxicity to fish was not considered an issue in the region until the early 1980's. Previously the Al_i in Nova Scotia was thought to be complexed with the organic matter produced by the many wetlands located in the province and thus rendered biologically inert (Clair et al, 2007). However recent studies have determined that aluminum toxicity is currently a threat to the fish in SWNS and that ionic aluminum levels often exceed the aluminum toxicity standards established by the European Inland Fisheries Advisory Commission (EIFAC) at 15 ug L^{-1} (Howells et al., 1990; Dennis and Clair, 2012; Macleod et al., 2015). Aluminum toxicity further complicates the acidification issue in SWNS and increases the importance of finding a viable mitigation solution.

The acidic conditions in SWNS are especially concerning for the SU designatable unit of Atlantic salmon who were listed as endangered by COSEWIC (DFO, 2013). Acidification is the most serious threat to the SU salmon population. The salmon have been extirpated from 13 extremely acidified rivers (pH <4.7) in Nova Scotia and are severely impacted in rivers with pH 4.7-5.0 (DFO, 2013). Population modelling for two of the largest populations within the SU designatable unit (LaHave and St. Mary's rivers) indicates a high probability of extirpation (87% and 73%, respectively) in 50 years if conditions remain unchanged. More positively, models for the LaHave River show that a 20% increase in habitat quality can reverse the risk of extirpation risk from 87% in 50 years to 21% (DFO, 2013).

Human intervention is required in SWNS in order to protect the aquatic ecosystem and sensitive species such as the SU Atlantic salmon. The goal of mitigative measures in acidified areas are commonly species specific (Clair and Hindar, 2012). The federal government and community groups are interested in improving habitat quality for the SU Atlantic salmon in SWNS in order to decrease the risk of extirpation (DFO, 2013; Gibson and Claytor, 2012). Additional reductions in sulphur emissions across central North America is the primary method to avoid further acidification of freshwater systems in SWNS but unfortunately it is not a top priority for the United States or Canada at this time. However liming methods can be used to mitigate acidification in SWNS and improve habitat quality for the SU salmon in the region.

There are several methods to liming that improve pH and alkalinity including in-stream liming, the addition of base cations directly to the water, and terrestrial liming, the addition of base cations to the soils. The only in-stream liming project in Nova Scotia is the West River Sheet Harbor project; although the project has been effective at improving water quality and increasing pH, it is not well supported by the federal government and therefore the project may be shut down in the near future. Alternatively the federal government and community groups are interested in terrestrial liming because it is low maintenance and sustainable over time as studies from Europe have shown it to be effective at improving water quality for decades without the need for reapplication (Hindar et al, 2003; Dalziel et al., 1994; Yan et al., 1991). Studies have also indicated that the effectiveness of terrestrial liming is variable depending on location (Hindar et al., 2003; Hindar and Wright, 2005; Sterling et al., 2014-a).

The decision on where and how much to lime is crucial to the success of terrestrial liming in increasing pH and improving habitat quality for the SU Atlantic salmon. When selecting sites to lime, considerations need to be made for attributes that support effective liming and the SU salmon population. The biophysical and chemical attributes of a site need to be considered as well as the biological and life cycle of the SU salmon in order to lime a site in which improving water quality will increase the population. There is a need for an extensive assessment of potential terrestrial liming sites in SWNS to support informed decision-making regarding what sites have the most promise for effective liming and help reduce the probability of SU salmon extirpation.

1.3. Knowledge Gaps

There is a strong consensus in the literature regarding acidification as the primary limiting factor to the Atlantic salmon (Watt et al, 1983; Peterson et al, 1980; Lacroix et al, 1987; Lacroix and Townsend, 1987; Kure et al, 2013; DFO, 2013) but discrepancies are present when it comes to what agent of acidification is detrimental to salmon in SWNS. Until recently low pH was believed the primary limiting factor for salmon in SWNS. Aluminum toxicity was not considered an issue in Nova Scotia because the Al_i was believed to be complexed with natural organic acids produced by wetlands, which are abundant in Nova Scotia (Clair et al, 2007). However, recent studies have found that aluminum toxicity is currently an issue in SWNS and often exceeds the EIFAC's aluminum toxicity threshold (Howells et al., 1990; Dennis et al, 2012; Macleod et al., 2015). Therefore, although the literature confirms that acidification is a major contributor to the SU Atlantic salmon population declines, whether that is through low pH alone or in combination with aluminum toxicity is still unclear.

Terrestrial liming has been widely accepted as an effective mitigative method to increase pH and alkalinity in freshwater systems (Jenkins et al, 1991; Howells et al., 1995; Traaen et al, 1997; Hindar et al, 2003; Clair and Hindar, 2005). There have been many terrestrial liming studies in Norway (Hindar et al., 2003; Traaen et al. 1997), Sweden (Westling and Zetterberg, 2007) and Whales (Jenkins et al., 1991) that show terrestrial liming improves pH, Ca^{2+}, Mg^{2+} and ANC while decreasing Al_i concentrations. These studies have predicted that water quality improvements from terrestrial liming will last upwards of 10 to 50 years without the need for reapplication (Jenkins et al., 1991; Hindar et al 2003). However, there is a lack of terrestrial liming research in Canada. The only study on terrestrial liming in Nova Scotia is the current experimental liming project at Maria Brook, a small catchment located within the Gold River Watershed in New Ross, Nova Scotia (Sterling et al, 2014-a). Studies from Europe have shown that the effectiveness of terrestrial liming varies greatly based on location (Hindar et al., 2003; Yan et al., 1991), therefore it is important to thoroughly research and identify sites in SWNS that will support effective terrestrial liming.

Terrestrial liming site selection is not documented in the literature, despite the numerous published papers focused on understanding the effects of terrestrial liming on freshwater systems (i.e., Dalziel et al., 1994;Fraansman and Nihlgaard, 1995; Traaen et al., 1997; Hindar et al., 2003). Much of the literature for terrestrial liming is from Sweden and Norway; the selection of terrestrial liming in these regions are focused on how sites may fit into a liming strategy rather than if a site is suited in itself. The terrain in Norway and Sweden is more suited to support effective liming because of their relatively steep slopes and high discharge rates; this ensuring well saturated soils and good contact between runoff and liming material due to surface/subsurface flow and thin soil cover indicating that only a small fraction of rainwater enters deep groundwater/aquifers (personal communication with Dr. Atle Hindar). Alternatively the effectiveness and feasibility of terrestrial liming in Nova Scotia likely varies by location due to a variety of physical and economic site specific factors. For example regions underlain by the Halifax Formation, a bedrock composed of pyritic slate, are at risk for Acid Rock Drainage (ARD). ARD is the leaching of sulfuric acid caused by exposure of sulphide-containing rock to air or water; this will acidify nearby freshwater systems. A comprehensive analysis of potential sites is required in the early planning stages of terrestrial liming projects in Nova Scotia to increase the probability of effective liming.

A report by the Mersey Tobeatic Research Institute (MTRI) used a Geographic Information Systems (GIS) approach for identifying liming sites within the Gold, LaHave and Medway watersheds in SWNS (Toms et al, 2010). This was the first and only assessment of liming sites that have been conducted. The assessment considered three of the 13 priority watersheds for the SU Atlantic salmon, as identified by the Southern Upland Collaborative Projects Working Group in October 2013. The sites within each watershed were selected through consultation with local anglers, despite recommendations on earlier versions of the project for a more quantitative analysis of the catchment size. Although the MTRI assessment is a good baseline reference for future projects using GIS to identify catchments for terrestrial liming in the region, there is a need for a more comprehensive and quantitative assessment that includes all 13 SU salmon priority watersheds.

1.4. Research Goals and Objectives

The objective of my research is to decrease the risk of SU salmon extirpation in SWNS by increasing the effectiveness of terrestrial liming through the identification of the best locations to lime and the information needed for effective liming. This research meets the need for an extensive assessment of terrestrial liming sites within the region. A sub-goal is to provide information to support the development of a Terrestrial Liming Guidebook that will summarize the top priority catchments for terrestrial liming in SWNS; the Guidebook will be publically available through the Bluenose Coastal Action Foundation (BCAF). The Guidebook can be used by stakeholders and decision makers to help make informed decisions about where to terrestrial lime.

My research builds upon MTRI's method by broadening the study area to all 13 priority watersheds and including site selection criteria that support effective liming and the SU salmon population. I use several of MTRI's selection criteria such as connectivity, the distance from the catchment to the mouth of the main river. In addition to MTRI's selection criteria I have identified and used important criteria crucial for the feasibility of liming and attributes that support the SU salmon. MTRI selected catchments within the Gold, LaHave and Medway River watersheds based primarily on angler consultation (Toms et al., 2010). Alternatively, my research is a more systematic and quantitative analysis to identify catchments using SU population parameters. My research provides more information to aid in the selection of terrestrial liming locations that support effective liming and the SU population.

My main research questions are:

1. What are the catchments that have the most promise for effective response to terrestrial liming and will best support the Southern Upland Atlantic salmon in South Western Nova Scotia?
2. What are the key information needs for improved terrestrial liming catchment selection in Nova Scotia?

The spatial scope of this study is limited to the 13 priority watersheds identified by the Southern Upland Collaborative Projects Working Group (Figure 1). This research began May, 2014 and was continued to April, 2015. Budgetary constraints are the primary limiting factor for my research. The financial constraints of this project limit the scale and detail that is included in the assessment.

1.5. Summary of Approach

I have developed a Simon's bounded rationality based decision model (Simon, 1972) to identify the top priority catchments for terrestrial liming within the 13 SU salmon priority watersheds using GIS (ArcMap 10.1, ArcHydro) and stakeholder consultation as primary research tools. I have developed a set of exclusionary and prioritization criteria that include site attributes that are either necessary for the success of terrestrial liming or support an increase in the SU salmon population. Site scoring methods based on the prioritization criteria are used to rank and identify the top priority catchments for terrestrial liming within the study area.

2. Literature Review

This literature review will focus on acidification research from the last several decades, with a more detailed review of research within South Western Nova Scotia (SWNS) from the early 1970's onward. Research regarding acidification and aluminum toxicity to fish in SWNS will be synthesized and discrepancies between different studies discussed and evaluated. Different acidification mitigation methods will be briefly compared with a focus on terrestrial liming techniques and liming site selection methods. Previous terrestrial liming research will be explored with a focus on Sweden and Norway as they are the leaders in liming research. Important knowledge gaps in acidification and terrestrial liming research will be identified through this literature review focusing on the need for catchment prioritization methods for terrestrial liming.

2.1 Freshwater Acidification

Acidification was first identified as an issue in Scandinavia and Eastern Canada in the 1970's. The study of acidification peaked in the late 1980s and has since dwindled off (Figure 1).

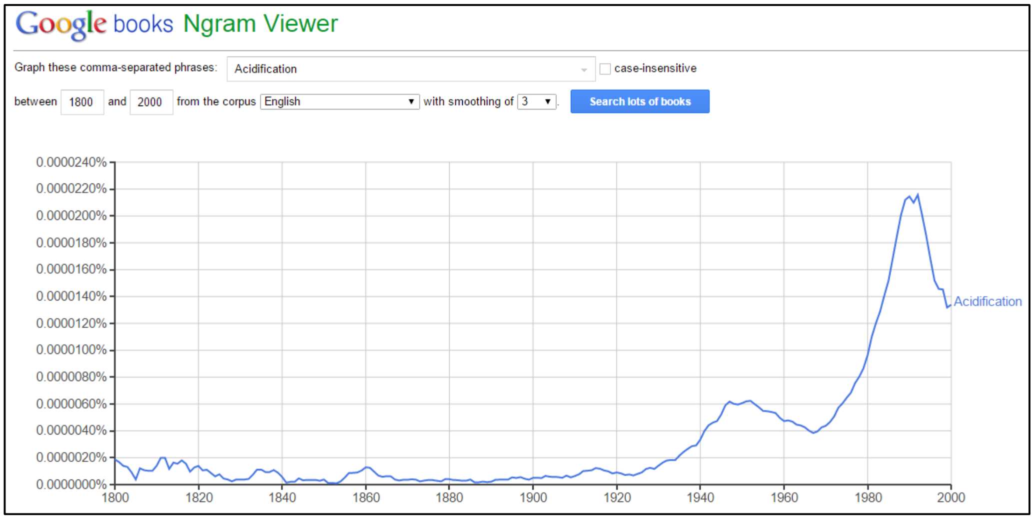


Figure 1. Google Nygram Viewer graph indicating number of books published annually with a title containing the word 'acidification'. Note the increase in the late 1970's, early 1980's and peak in the late 1980's, early 1990's.

Freshwater acidification occurs when surface waters contain more negatively charged acid anions (sulfate, nitrate, chloride) than positively charged cations (Clair et al., 2007; Brodin, 1995; Watt et al., 1979) and is characterized by a low pH conditions and the resulting mobilization of metals (i.e. Al_i) (Bache, 1986; Cronan and Schofield, 1979; Dennis and Clair, 2012). Acidification was first recognized as a serious threat marked by a series of acidification mitigation programs, mostly located in European countries such as Sweden [i.e., Integrated Studies on the Effects of Liming (ISEL); Nyberg, 1995] and Norway (i.e., Monitoring Programme of Acidification; Raddum and Fjellheim, 1995), and the United Kingdom [i.e., Surface Water Acidification Project (SWAP), Battarbee and Renberg, 1990]. North America recognized the issue of acid rain marked by changes in regulations that cut emissions that contribute to acidification [i.e., 1990 amendments to the Clean Air Act (1963) (EPA, 2013)].

There are several factors that can contribute to surface water becoming acidified. The most common cause is acid deposition or precipitation, also known as acid rain. The two anions associated with acid precipitation are sulphate (SO_4^{-2}) and nitrate (NO_3^-). These chemicals are produced through the oxidation of sulfur dioxide (SO_2) and nitrogen oxide (NO_x) which are released into the atmosphere through the burning of fossil fuels. The acid rain product of SO_2 and NO_x emissions are often deposited far from the pollution source (Stoddard et al., 1999; Environment Canada, 2012; Clair et al, 2005). In addition to acid deposition, the regional bedrock and soils are largely determinate of the resulting surface water pH. Regions with low ANC are particularly vulnerable to acidification with acid deposition. Severe acidification is likely to occur in regions subject to acid deposition in conjunction with bedrock and soils with low ANC (Clair et al., 2005).

Freshwater acidification is detrimental to aquatic biota, particularly fish species, because of the low pH conditions and the resulting Al_i mobilization. Natural occurring aluminum can become toxic to fish species in acidic regions when the aluminum changes to the ionic form. The availability of Al_i is pH dependent and occurs between pH 5.0 to 6.0 (Poleo, 1995). Within a pH range of 5.0 to 6.0 the Al_i toxicity threshold is 15 ug L^{-1} as set by the European Inland Fisheries Advisory Commission (EIFAC); within this pH range Al_i levels above the threshold are toxic to fish species. Aluminum toxicity is caused when Al_i forms a complex with the negative ions of the fish gills causing excess mucus formation and respiratory impairment (Dennis and Clair, 2012).

Research dating back to the early 1980's confirm that acidity is a limiting factor for fish species, especially during sensitive early life stages. Peterson et al., (1980) found Atlantic salmon eggs were delayed or prevented in waters with a pH of 4.0-5.5 and induced at pH 6.6-6.8. Similarly Lacroix et al., (1985) found a significant difference in mortality rates of salmon fry, the life stage where they are just capable of feeding themselves, in pH 5.0 waters (70% mortality) compared to pH 6.2 waters (4% mortality). In another study Lacroix et al., (1987) again confirmed the theory that acidic conditions are limiting to fish by observing salmon parr, juvenile fish, in rivers with different pH conditions; he found that all parr died in streams where pH decreased below 4.7. A more recent study (2013) found that the microDNA of salmon are altered when exposed to acidic aluminum-rich waters, suggesting that the causality of toxicity from low pH and aluminum may be more complex than previously thought (Kure et al., 2013).

In addition to freshwater acidification, terrestrial acidification is also an issue in regions with low ANC and high acid deposition. Terrestrial acidification is a global threat to vegetation and is caused by acid deposition decreasing soil pH. Acidified soils are characterized by low pH, low base cations concentrations and primary nutrients such as Ca^{2+} and Mg^{2+}, increased metal mobilization and decreased nitrification and organic matter decomposition rates (Johnson et al., 1982; Azevedo et al., 2013; Bobbink et al., 2010). Terrestrial acidification can result in changes in nutrient cycling and decreased availability of primary nutrients to vegetation which can lead to decreased fitness (i.e., reduction in biomass and root growth and unsuccessful germination and regeneration) (Azevedo et al., 2013; Falkengren-Grerup, 1986). In addition, acidification can cause competitive exclusion by acid-tolerant species who thrive in low pH soils (Azevedo et al., 2013; Falkengren-Grerup, 1986). Acidification is detrimental to both terrestrial and aquatic ecosystems through decreasing productivity rates and the fitness of terrestrial and aquatic organisms.

2.2 Acidification research in SWNS

SWNS has some of the most acidified waters in North America (Stoddard et al., 1999; Clair et al., 2007). Despite the United States and Canada's reductions in emissions (76% and 36%, respectively, since 1990) SWNS has not seen improvements in pH (EPA, 2013; Environment Canada, 2012; Stoddard et al., 1999). The lack of water quality improvements are unique to the SWNS as most acidified regions across North America and Europe have experienced widespread recovery (Stoddard et al., 1999). Unfortunately water quality is not predicted to improve naturally for another 60 years if conditions remain the same (Clair et al., 2004).

There are several interacting and contributing factors involved in the chronic acidification and lack of recovery in SWNS. First, the prevailing winds travelling west to east across Canada transports emissions, such as SO_2, east across the country where they are deposited in the form of acid deposition (Clair et al., 2007). Second, the regional bedrock in SWNS has low ANC and is ineffective at buffering acidic inputs. The bedrock in SWNS consists of the Cambrian to Ordovician Meguma Group which has two divisions: the Goldenville formation and overlying Halifax formation. In addition, the South Mountain Batholith, a granitic batholith, overlies a large portion of the Meguma Group in SWNS (White, 2002). These rock formations have low ANC indicating that that they are composed of materials that are low in cations (e.g. Ca^{2+}, Mg^{2+}) and are slow weathering. The Goldenville formation consists of greywacke and metamorphic equivalents (Watt et al., 1983; White, 2002) and the Halifax formation consists of pyritic slate and has particularly low ANC. ARD associated with the erosion of the Halifax formation is particularly detrimental as sulfuric acid inputs can further acidify a river (Fox et al., 1997). In connection with the bedrock, is the thin alkaline-poor soils formed from the slow weather of the underlying rock rendering them with low ANC (Watt et al., 1983; Fox et al., 1997; Sterling et al., 2014-a).

The chronic acidification in SWNS is detrimental to the aquatic biota inhabiting the watersheds in the region. Earlier studies have determined that low pH conditions are the only acidification related limiting factor to fish species in SWNS, concluding that aluminum toxicity was not an issue in the province because Al_i forms a complex with organic matter, which is abundantly produced by wetlands (Peterson et al., 1989; Lacroix and Townsend, 1987). When Al_i forms a complex with organic matter it is no longer biologically available thus not an issue for fish (Baker and Schofield, 1982; Driscoll et al., 1980). It was not until recently that this was questioned by the work of Dennis and Clair (2012) who found that Al_i values exceed the aluminum toxic threshold of 15 ug L^{-1} in seven rivers in SWNS. Further research by MacLeod et al., (2014) identifies that the aluminum levels are increasing in SWNS.

In 1990 the aluminum toxicity threshold, above which Al_i is considered toxic to fish species, was reduced from 50 ug L^{-1} to 15 ug L^{-1} (Howells et al., 1990). This brings into question the conclusions on aluminum toxicity in SWNS from before 1990 where research may have found the Al_i concentration below the previous 50 ug L^{-1} but above the current 15 ug L^{-1}. This is the case for Lacroix et al., (1987) who studied parr survival under different pH conditions and concluded that the limiting factor to parr is low environmental pH; Lacroix and colleagues did not consider aluminum toxicity because Al_i levels did not exceed 50 ug L^{-1}. Alternatively, four of the five rivers sampled had mean Ali values above the 15 ug L^{-1} toxicity threshold, suggesting that aluminum toxicity may have been a contributing factor to parr mortality. The research by Dennis and Clair (2012) and MacLeod et al., (2014) and the review of earlier research, before the reduction in the aluminum toxicity threshold, suggest that the toxicity to aquatic biota in acidified environments is more complex than previously thought. Low environmental pH can in itself be toxic but Al_i will be mobilized and may be toxic in waters with a pH between 5.0-6.0 (Poleo, 1995) therefore increasing pH above this range will avoid toxicity from both of these agents.

2.2.1 Effects on Southern Upland Atlantic salmon

Acidification is one of the primary limiting factor for the Southern Upland (SU) Atlantic salmon designatable unit, which is evaluated as endangered by COSEWIC in 2010 (Lacroix et al., 1985; Lacroix et al., 1987;COSEWIC, 2010; DFO, 2013). The abundance of the SU salmon have decreased significantly from the 1980's and 1990's with annual abundances in four indicator rivers reduced by 88% to 99% from the 1980's. River specific extirpation is found to have occurred in 13 highly acidified rivers (pH <4.7) which historically had salmon presence (DFO, 2013). Population viability modelling for two of the larger populations (LaHave and St. Mary's river) indicate a high probability of extirpation (87% and 73%, respectively) within the next 50 years (DFO, 2013). More positively, population models for the LaHave River show that a 20% increase in habitat quality can reverse the risk of extirpation risk from 87% to 21% in 50 years (DFO, 2013). The slow natural recovery from acidification in SWNS and high probability of extirpation of the SU salmon highlights the need for mitigative methods for acidification in critical SU salmon catchments.

2.3 Liming

The best way to avoid acidification is to decrease SO_2 emissions, which deals with the problem at the source (Olem, 1991). Following the recognition of acid rain, acidification and its relationship to sulphur emissions, SO_2 emissions have been dramatically reduced (EPA, 2013; Stoddard et al., 1999; Environment Canada, 2012). Reduced SO_2 emissions have resulted in an improvement in water quality in most regions across areas of North America and Europe (Skjelkvale et al., 2005) but this improvement is slow, especially in some regions such as SWNS (Stoddard et al., 1999; Clair et al., 2007). The only mitigative method for acidification is liming, the addition of base cations to an acidified system (Olem, 1991). In regions of slow recovery containing acid sensitive species with low resilience to withstand prolonged periods of acidification, it is necessary to lime to mitigate the negative effects of acidification. Liming can improve water quality in systems that may otherwise take decades to recover naturally following the reduction in SO_2 emissions; this is particularly important for acid sensitive species that may be extirpated from these systems if improvements are not immediate.

2.3.1 Liming Methods

There are several different buffering components and liming methods that can be used to mitigate acidification in freshwater systems. Although limestone ($CaCO_3$) is the most common buffering material, other materials exist (table 1). Limestone is the most common because it is relatively inexpensive, has been well studied and is readily available in most areas because of its use in agriculture (Dennis and Clair, 2005).

Table 1 Theoretical neutralization equivalents of the main buffering materials used for terrestrial liming. Values are relative to limestone $CaCO_3$ (table from Olem, 1991).

Common name	Formula	Theoretical neutralization equivalent (%)
Limestone	$CaCO_3$	100
Dolomite	$CaCO_3$-$MgCO_3$	109
Sodium carbonate	Na_2CO_3	94
Sodium bicarbonate	$NaHCO_3$	119
Calcined lime	CaO	179
Calcined dolomite	CaO-MgO	207
Hydrated lime	$Ca(OH)_2$	135
Dolomitic hydrate	$Ca(OH)_2$-MgO	175
Pressure dolomitic hydrate	$Ca(OH)_2$-$Mg(OH)_2$	151
Caustic soda	$NaOH$	125

The three most common liming methods used are in-stream liming, lake liming and terrestrial liming; a less common method, sediment liming, is also worth noting (table 2). All liming methods used to mitigate acidification have the objective of improving surface water quality and increasing pH. There are particular methods that are used for only one type of surface water (i.e., lake liming used to improve the water quality of lakes) whereas other methods can be applied to multiple surface waters (i.e., terrestrial liming used to improve both lake, stream and larger river systems). The decision on what liming methods to use is dependent on several factors including, but not limited to, what the surface water target is, the current water chemistry, the surrounding topography and the set budget and duration of the liming project.

Table 2. Different liming methods with brief description, improvement duration and example projects for each. Description and typical duration from Clair and Hindar (2005)

Liming method	Description	Improvement duration
In-stream liming	Addition of buffering materials directly to running waters, typically through the use of a lime doser.	Improvement immediate, lasting until doser is removed.
Lake liming	Addition of slurried or fine grain buffering materials directly onto the surface of a lake	Improvement immediate. The duration of the improvements depends on the flushing rate of the lake, reapplications necessary when liming products are lost. [can be as frequent as every 1-2 years (Hindar and Wright, 2005) or as infrequent as 4-16 (Yan et al., 1995)]
Terrestrial liming	Addition of buffering material to the catchment or drainage area of a river or lake.	Improvements immediate. Usually long lasting with low reapplication frequency. [reapplication can be as infrequent as every 15-50 years (Dalziel et al., 1994; Hindar et al., 2003)]
Sediment liming	Addition of gravel sized particles of buffering materials to stream sediments	Improvement immediate but usually decreases within a few weeks (Watt et al., 1984; Hindar et al., 2003). Reapplication often.

Terrestrial liming has a broad potential because it applies the liming material directly to the soils which can buffer the acid and metal leaching at the source (Clair and Hindar, 2005). Terrestrial liming is the only liming method that applies lime directly to the soils of the catchment surrounding the target acidic water system. It adds calcium (Ca^{2+}) and other base cations to the soils allowing for ion exchange with the incoming hydrogen (H^{+}) molecules associated with acid inputs thus increasing ANC (Dennis and Clair, 2012). This is the only liming method targets metal mobilization, such as $Al_{i,}$ at the Critical Source Areas within catchments before they enter the river system (Fransman and Nihlgaard, 1995; Clair and Hindar, 2005).

There are two types of terrestrial liming that vary depending on where the lime is applied to a catchment. Whole catchment liming is the application of base cations to the entire catchment of an acidified river. Alternatively wetland liming is the application of base cations specifically to the wetlands or hydrological source area within a catchment (Jenkins et al., 1991). It is important that the critical source area of target parameters that influence salmon health are limed in both application methods (Sterling et al., 2014; Bradley and Ormerod, 2002).

Terrestrial liming has long lasting water chemistry improvements with no maintenance and a lower reapplication frequency when compared to the other three methods of liming:

1. An advantage of terrestrial liming method over in-stream lime dosing is that it does not require an expensive doser, regular maintenance or the provision of lime (Clair and Hindar, 2005). The lime is applied to the catchment and reapplication of lime may not be necessary for another 15 to 50 years (Dalziel et al., 1994; Hindar et al., 2003), if a sufficient dosage of lime is applied.
2. There are two major problems associated with sediment liming that makes terrestrial liming a more reliable liming method. Studies have found that the lime particles quickly become covered in organometallic coatings thus decreasing the lime dissolution into the water (Watt et al., 1984; Clair et al., 2005). In addition to this, during major storm events or even regular flow, the buffering material added to the sediments can move downstream with the bed load, therefore not improving water quality in the targeted portion of the river.
3. The issue with lake liming is the loss of lime through outlet waters, which is dependent on the flushing rates and retention time of the lake, and sedimentation of lime particles in the lake bottom (Clair and Hindar, 2005). The reapplication frequency varies in the literature with some studies finding that liming needs to be repeated as often as every 1 to 2 years (Hindar and Wright, 2005) with others studies finding every 4 to 16 years (Yan et al., 1995; Clair and Hindar, 2005). The longest improvement duration documented for lake liming (16 years) is much lower than that for terrestrial liming (50 years) indicating that more frequent reapplication may be required for lake liming. An additional issue with lake liming is poor mixing of cold, acidic snowmelt which typically forms a layer at the lake surface (Clair and Hindar, 2005).

For terrestrial liming to be successful in improving water quality the correct dosage and buffering material must be applied to the catchment (Clair and Hindar, 2005). A variety dosage rates have been effective at improving water chemistry, with improvement duration lasting anywhere from 1-2 years (Yan et al., 1991) to up to 50 years (Hindar et al., 2003) without the need for reapplication. A common dosage rate in the literature is 3 t/ha (Traaen et al., 1997; Hindar et al., 2003; Fransman and Nihlgaard, 1995). Other dosage rates have been used, for instance Anderson et al. (1995) limed Prästvallsbäcken stream in Sweden using 3 different applications once every 2 years from 1984 to 1990 with dosages ranging from 6.4 t/ha to 31.5 t/ha. The dosage rate varies depending on the type of terrestrial liming (i.e., whole catchment or wetland), the baseline water chemistry, the target parameters and the location; preliminary research should be conducted in a region to understand necessary dosage application rates before liming occurs.

Application cost is usually the greatest limiting factor to terrestrial liming projects with application usually done by helicopter (Clair and Hindar, 2005; Fransman and Nihlgaard, 1995; Anderson, 1995; Traaen et al., 1997), the application cost can be reduced using ground application methods. For example, to reduce application cost, Sterling et al. (2014-a) used ground application methods to spread powdered limestone throughout the Maria Brook experimental liming catchment in New Ross, Nova Scotia with the help of students from New Germany Rural High School; this had the added benefit of educating the students about acidification and the benefits of liming. Although terrestrial liming application can be expensive, alternative methods of application can make it more affordable for community groups that have limited project budgets.

Terrestrial liming has been shown to improve terrestrial productivity in addition to water chemistry. Terrestrial liming has been used to improve soil quality in both forest and agricultural landscapes (Hüttl and Schneider, 1998; Scott et al., 2000). The addition of buffering mateial to an acidified landscape, increases soil pH, base cation concentrations, including primary nutrients like Ca^{2+} and Mg^{2+}, and decreases metal concentrations (Smallidge et al., 1993). Terrestrial liming of acidified landscapes have been shown to increase nitrification and decomposition rates and increase the abundance and richness of plant, invertebrate and bird species (Smallidge et al., 1993; Pabian and Brittingham, 2007). Unfortunately the liming of wetlands, or other naturally acidic environments, has been found to be detrimental to acid tolerant species such as Sphagnum mosses (*Sphagnum*), which thrive in more acidic conditions; the impact on the acid tolerant species found within wetlands needs to be considered during terrestrial wetland liming projects (Smallidge et al., 1993; Brown, 1988).

2.3.2 Terrestrial Liming Results

Sweden is one of the most severely acidified countries and also has the largest and most comprehensive liming program in the world (Nyberg and Thornelof, 1988); the Swedish

Government developed a trial liming programme in the late 1970's (National Swedish Board of Fisheries in 1976), shortly after the relationship between acid deposition and the acidification of freshwater systems was understood, and has since subsidized large-scale acidification programmes across the country (Henrikson and Brodin, 1995).

Terrestrial liming was used by Fransman and Nihlgaard (1995) who limed three acidified catchments in Hagfors, Central Sweden with 20 tonnes of limestone. A dosage rate of 3 t/ha was applied using helicopter application techniques. Fransman and Nihlgaard found a significant increase in pH, Ca^{+2} and ANC thus improving the water quality within these catchments. In a similar study Anderson (1995) also used helicopter application to lime the catchment of Prästvallsbäcken stream, Sweden. Unlike Fransman and Nihlgaar (1995), Anderson (1995) performed 3 applications, once every two years from 1984 to 1990, with varying catchment and dosage rates (6.4 to 31.5 t/ha). Despite the differences in catchments, application frequency and dosage rates, both studies found improvements in water quality with Anderson (1995) reporting a decrease in metal concentrations (aluminum and iron) and an increase in pH. These two studies from Sweden support the theory that terrestrial liming improves water quality, despite variation in study area, frequency and dosage rates.

In addition to Sweden, Norway is another country who has done a substantial amount of liming research also having implemented large-scale liming operations to mitigate acidification. Two particular studies of interest for terrestrial liming research have been conducted in Norway. Traaen et al., (1997) used helicopter application to lime the 25 ha Tjønnstrond catchment with 3 t/ha of powdered limestone. This resulted with a pH increase of 4.5 to 7.0 with improvements predicted to last for at least 20 years. A study with similar, but even longer predicted improvement duration, is that of Hindar et al. (2003). Using helicopter application, an 80 ha catchment was limed with 3 t/ha of coarse dolomite [$CaMg(CO_3)_2$]. Hindar et al. (2003) found that pH, Ca^{2+}, Mg^{2+} and ANC increased with a decrease in Al_i. Water quality monitoring for seven years post-liming showing that improvements remained and model simulations indicate that improvements may last for an additional 50 years. The results of research in Norway helps solidify terrestrial liming as a long-term stable method to improve water quality.

There has been significantly less liming research conducted in Canada in comparison with Sweden and Norway, despite Canada having regions of severe acidification. For instance, SWNS has some of the most acidified waters in North America and, although in-stream liming has been researched (i.e., West River lime doser; Atlantic Salmon Federation, 2013), only one small experimental terrestrial liming site exists in the region. The only experimental liming site documented in the literature for Canada is located in the Maria Brook catchment, a small catchment in New Ross, Nova Scotia. Three treatments of powdered limestone have been applied each spring since 2012 with a cumulative amount of 120 t applied. Results have not shown improvements in water quality yet but the research is still ongoing (Sterling et al., 2014-a). It is evident in the literature that terrestrial liming research in Canada is far behind that of Norway and Sweden and the effects of terrestrial liming in SWNS are not well characterized.

2.3.4 Terrestrial Liming Site Selection

The success of terrestrial liming on improving the water quality of an acidified river, is strongly influenced by the attributes of the liming catchment and the target species. Most liming projects, unless primarily for research, have the objective of restoring aquatic habitat for a particular species and therefore, in addition to environmental attributes of a catchment, the attributes necessary for the target species (i.e., breeding habitat) must be considered when selecting catchments for liming. For example, the surface water must be acidified for liming to increase pH and the catchment must be within the target population's range to have an effect on the population. Most projects across North America and Europe have been conducted to help restore fish populations (Traaen et al., 1997; Hudy et al., 2000) with even the studies for scientific purposes having a broader goal of improving habitat for a particular species [i.e., Sterling et al., (2014-a) with the SU Atlantic Salmon]. The decision on what site to lime is a crucial to the success of the liming project in improving water quality and increasing suitable habitat for the target species.

The site selection process for terrestrial liming is absent from the literature, with no peer-reviewed articles on the subject published. The only research on terrestrial liming site selection is a report by the Mersey Tobeatic Research Institute (MTRI). This report considers both catchment attributes and the SU salmon target species and uses a Geographic Information Systems (GIS) approach to select and prioritize catchments within three watersheds (Gold, LaHave and Medway watersheds) in SWNS. Unfortunately the MTRI assessment lacks a quantitative assessment of catchment size and does not include key catchment and SU population attributes.

The difficulty in identifying sites that support effective terrestrial liming with the objective of increasing the SU population is that those two objectives have contradicting optimum liming sites. The optimum terrestrial liming catchments have a small area and therefore support the greatest improvement in water chemistry with the least amount of lime. Alternatively, the optimum terrestrial liming sites for the SU salmon are larger catchments that can support the most productivity and that are located close to the mouth of the main river which increases the probability that the salmon will rear within the catchment. The identification of catchments that supports both effective liming and the SU salmon involves the optimization between the two contradicting objectives, making it more difficult than pursuing one of the two objectives independently. A a comprehensive study to identify sites that both support effective liming and the SU salmon is needed in SWNS to provide information to decision-makers on what sites are best to lime in order to meet the conflicting objectives.

2.4 Decision-Based Models Using Geographic Information Systems

Decision-based models have been used by decision-makers as a tool for site selection for centuries, using it to answer questions from where to settle to what are the best locations for a nuclear power facility? There are three concepts that decisions-makers have to work under:

1. There is a limited amount of information available and that this information will have a level of uncertainty and unreliability.
2. The decision-makers ability to make a decision is bound by human capacity.
3. Most decisions are limited by time constraints.

Working under these three concepts is what makes decision-making a difficult task. The Simon's bounded rationality model is used to help make decisions where information may be unavailable or uncertain (Simon 1972). The Simon's bounded rationality can be used to make decisions based on optimization, making the best decision under a given set of constraints such as limited data availability or limited time. Decisions where real life complexity and uncertainty makes it difficult to compare and contrast options requires a model that can optimize using approximations or indexes of real world phenomenon. The Simon's bounded rationality model is an appropriate tool to base a decision-based model on as it allows the achievement of goals within the limits that are unavoidable in real life decision-making.

Geographic Information Systems (GIS) is computer system designed to capture, store, analyse, manipulate data, helping us to understand relations, patterns, and trends (ESRI, 2014). GIS has been used as a decision support technology since the development of the Canadian Geographic Information System (CGIS) in the 1960's (Jankowski, 1992) and is an important decision-making tool for site selection problems in many research fields. The concept of using basic mapping ideas for site suitability stemmed the work of McHarg (1969) who developed the method of preparing and overlaying thematic maps to view composite configuration in order to choose a site best suitable for a specific function based on a pre-existing set of interacting factors (Sumathi et al., 2007).

GIS technology is an important tool for land use suitability analysis for site selection in many research fields. GIS is readily used when investigating where to place a development, such as a waste management facility (Sumathi et al., 2008; Feo and Gisi, 2014), that has certain environmental and human health ramifications that need to be considered. GIS can also be used to identify the optimal sites for different renewable energies; for example Aydin et al., (2013) identified sites for a hybrid wind solar-PV energy system by using GIS to identify sites suitable for wind turbines and solar-PV separately then overlying these sites to identify the most feasible location for a hybrid system.

Literature from the last decade suggest that GIS is becoming an important tool for site selection in conservation. GIS can be used to identifying priority areas for conservation by looking at species richness and rarity at different spatial scales (Woodhouse et al., 2000). Another conservation use for GIS is the identification of critical habitat for endangered or at risk species so that habitat protection or improvement efforts can be aimed at the sites most critical for the population. GIS technology has become a crucial tool in identifying critical habitat for conservation by allowing the spatial analysis of multiple data types and the prioritization of potential sites to ensure that the top priority site is selected.

The use of GIS for site selection in conservation is a relatively new process therefore it has some weaknesses that need to be recognized. The GIS analysis and output are only as accurate as the input data (Brambilla et al., 2009; Boitani et al., 2011). When using GIS for an analysis, for example on habitat requirements and species preference, the results are only as reliable as the data collected supporting the habitat and preference assumptions (Brambilla et al., 2009). This becomes relevant in population level conservation when deciding the minimum area required to sustain a particular population, a crucial step in the conservation process where if you under estimate the habitat required, the population will not persist or if you over estimate you waste limited resources. Brambilla et al., (2009) showed the discrepancy between using coarser landscape scale and finer territorial scale habitat assessments for the threatened red-backed shrike (*Lanius collurio*) in the Lombardy region, Italy. Both scales of analysis appear to be useful in shrike conservation: the landscape scale assessment provided information on areas heavily populated by shrike, even some previously unknown areas, allowing the analysis on habitat connectivity between patches and/or populations whereas the territorial level assessment at the site level provided insight into specific habitat preferences allowing for more informed site selection. Brambilla's study is an example of why caution needs to be taken when using GIS technology to identify and assess sites for conservation purposes through the careful documentation of any project assumptions and of the availability, accuracy and the researcher's confidence in the data used.

GIS provides a valuable tool for site selection for terrestrial liming by providing the means to conduct a regional-scale spatial analysis of site attributes that support a positive change in stream chemistry, as well as species specific conditions that support an increase in population with an improvement in stream quality. The first and only use of GIS technology for terrestrial liming site selection was done by the Mersey Tobeatic Research Institute (MTRI). MTRI used a GIS approach for choosing terrestrial liming sites in the Gold, LaHave and Medway watersheds (Toms et al., 2010). MTRI used site criteria to identify 11 sites located in the Gold, LaHave and Medway watersheds. Each site was ranked based on the selection criteria. The selection criteria used to prioritize the sites include salmon presence, recharge area, area of catchment owned by large land owners, minimum pH, Invasive species [Chain Pickerel (*Esox niger*) and Smallmouth Bass (*Micropterus dolomieu*) presence] and connectivity to the mouth of the primary watershed.

The MTRI report is the first study using GIS technology for terrestrial liming site selection and therefore, as with any new method, there are a few notable issues. The target species for this terrestrial liming project is not clearly stated in the MTRI report but it is assumed to be the SU

Atlantic salmon, based on the study area watersheds which are included in the SU salmon range and the use of salmon presence and invasive competitive species to the salmon. The SU Atlantic salmon population range includes rivers in Nova Scotia extending from the northeastern mainland, along the Atlantic coast and into the Bay of Fundy as far as Cape Split (COSEWIC, 2010) including 13 priority watersheds for the population identified by the Southern Upland Collaborative Workings Group in fall of 2013. The MTRI includes three of the 13 priority watersheds but does not assess the potential for terrestrial liming in the remaining 10 sites. Although recommendations from an earlier version of the report requested quantitative assessment of the size of the catchments is made at a watershed level, MTRI continued their assessment with previously identified sites based on angler suggestions because of limited technology. MTRI reported some data analysis restrictions due to hardware and software limitations which resulted in a partial analysis of two of the larger catchments because the Digital Elevation Model (DEM) raster layer for the whole catchment was too large. Although there are some clear problems in MTRI's methods their research represents a baseline study for using GIS as a decision-making tool in the assessment of potential terrestrial liming sites which can be referred to and improved upon.

There are no studies on the use of decision-based models for identifying catchments for terrestrial liming in a peer-reviewed journal. Therefore there is no methodology for terrestrial liming site selection, aside from the MTRI (2010) report, available in the literature. After contacting experts in the field who have conducted terrestrial liming research (i.e., Atle Hindar, Kevin Bishop and Stefan Löfgren) it was concluded that terrestrial liming site selection is not necessary in Norway and Sweden because most of the terrain is suited for liming. Site selection in Norway and Sweden is based on where the government would fund the project rather than what catchments would best support effective liming. Unlike in Norway and Sweden, SWNS does not have large regions suitable for terrestrial liming and therefore it is crucial to focus liming efforts on catchments that support effective liming and the target species.

2.5 Summary of Knowledge Gaps

The literature shows that, even though acidification in SWNS has been researched since the late 1970's, the issue is complex and that more research is necessary in the region to fully understand the underlying mechanisms, trends and relationships. There is a need for more aluminum research in Nova Scotia as recent studies have found Al_i concentrations in some SWNS rivers significantly higher than the aluminum toxicity threshold which suggests that it may be a limiting factor to fish in the region. There is a need for more extensive watershed level assessments including a provincial pH survey to better characterize acidification for terrestrial liming catchment selection and other watershed management application.

There has been little research conducted in Canada on terrestrial liming, with the exception of Sterling et al., (2014-a) research at the experimental liming site located in a small catchment in New Ross, Nova Scotia. Sterling et al., (2014-a) identifies the need for further research on the following topics in SWNS:

1. Creation of calcium budgets and their response to liming in order to understand how much applied limestone is taken up by vegetation and how much remains in the soil.
2. Completion of dosage calculations for terrestrial liming based on ANC and critical load exceedances
3. Examination of aluminum dynamics in the region to pinpoint the critical source areas (CSA) and to develop a more robust model for estimating ionic aluminum from readily measured parameters
4. Examination of spatial and temporal patterns of acidic episodes in SWNS
5. Evaluation of other composition and forms of limestone to be used in terrestrial liming

There is need for more research on terrestrial liming in SWNS in order to effectively mitigate acidification in the region and help restore critical SU Atlantic salmon habitat.

There is a need for a more comprehensive and quantitative analysis in SWNS. A regional-scale assessment of potential terrestrial liming catchments is needed in SWNS with the objective of improving water quality for the SU Atlantic salmon. The previous catchment identification model developed by MTRI did not consider key attributes crucial for effective terrestrial liming. For example, the assessment did not consider ARD, which is an issue unique to the region. In addition MTRI did not consider population attributes specific to the SU Atlantic Salmon. For example MTRI's study area only included three of the 13 priority watersheds for the SU salmon and did not consider critical salmon habitat requirements. A more comprehensive, regional scale multi-attribute decision model is needed that will consider both environmental factors that impact the effectiveness of liming and population attributes to identify catchments that best support the SU salmon. In addition, the key information required for improved terrestrial liming catchment selection needs to be clearly identified as a focus for future research.

3. Methods

3.1 Overview

The Simon's bounded rationality decision-based model is used to identify potential catchments for terrestrial liming in SWNS followed by prioritization using a scoring scheme similar to that used in MTRI's site selection report (Toms et al, 2010). The model involves the use of a set of indices for unknown variables where data is absent. Methods using indices in the absence of data is not uncommon in scientific research, for example Vörösmarty et al. (2010) used indices in assessing stressors in the analysis of Global threats to human water security and river biodiversity. The catchment prioritization model was developed using GIS technology (ArcGIS 10.1) and local knowledge gained through stakeholder consultation which largely influenced the selection criteria and assumptions of my research. The model involves exclusionary and prioritization criteria used to identify the optimum catchments for effective liming in SWNS that will best support the SU salmon. Exclusionary criteria are used to exclude regions within the study area that are not feasible for liming. The exclusionary criteria is followed by the identification of potential liming catchments within the remaining area using a quantitative assessment involving multiple SU population parameters. The identified catchments are then prioritized using a scoring scheme based on prioritization criteria. Stakeholder and expert consultation were important to the development and justification of the methods used for this research.

3.2 Study area

3.2.1 Selection of priority watersheds

One of the main objectives of this research is the identify catchments that will decrease the probability of extirpation for the SU salmon with water quality improvements, therefore the study area includes only watersheds that meet this objective. The Southern Upland Salmon Collaborative Projects Working Group identified 13 SU salmon priority watersheds in 2013. The Southern Upland Collaborative Projects Working Group is composed of stakeholders including government [Department of Fisheries and Oceans (DFO)], community groups, scientists and academics. The priority watersheds were selected based on the river and salmon population characteristics:

1. Salmon population consisted of a wild native strain of salmon
2. Salmon are present in the river – using the 2008 electrofishing data
3. The rivers has a mean annual pH > 5.1
4. There is an active group involved in the river to promote work and collaboration
5. The river is relatively large with respect to rearing habitat
6. It contributes to a geographic diverse group of priority watersheds (represents an ecodistrict not otherwise present or contributed to a broad geographic spread of river).

The 13 priority watersheds are:

1. Country Harbor
2. Gold River
3. LaHave River
4. Medway River
5. Moser River
6. Mushamush River
7. Musquodobit River
8. Newcombe Brook
9. Sackville River
10. Salmon River, Guysborough County
11. St. Mary’s River

12. Tusket River
13. West River, Sheet Harbor

These 13 priority watersheds are identified by fish biologists and other stakeholders with the Southern Upland Collaborative Projects Working Group as the units to focus conservation efforts for the SU salmon (Figure 2).

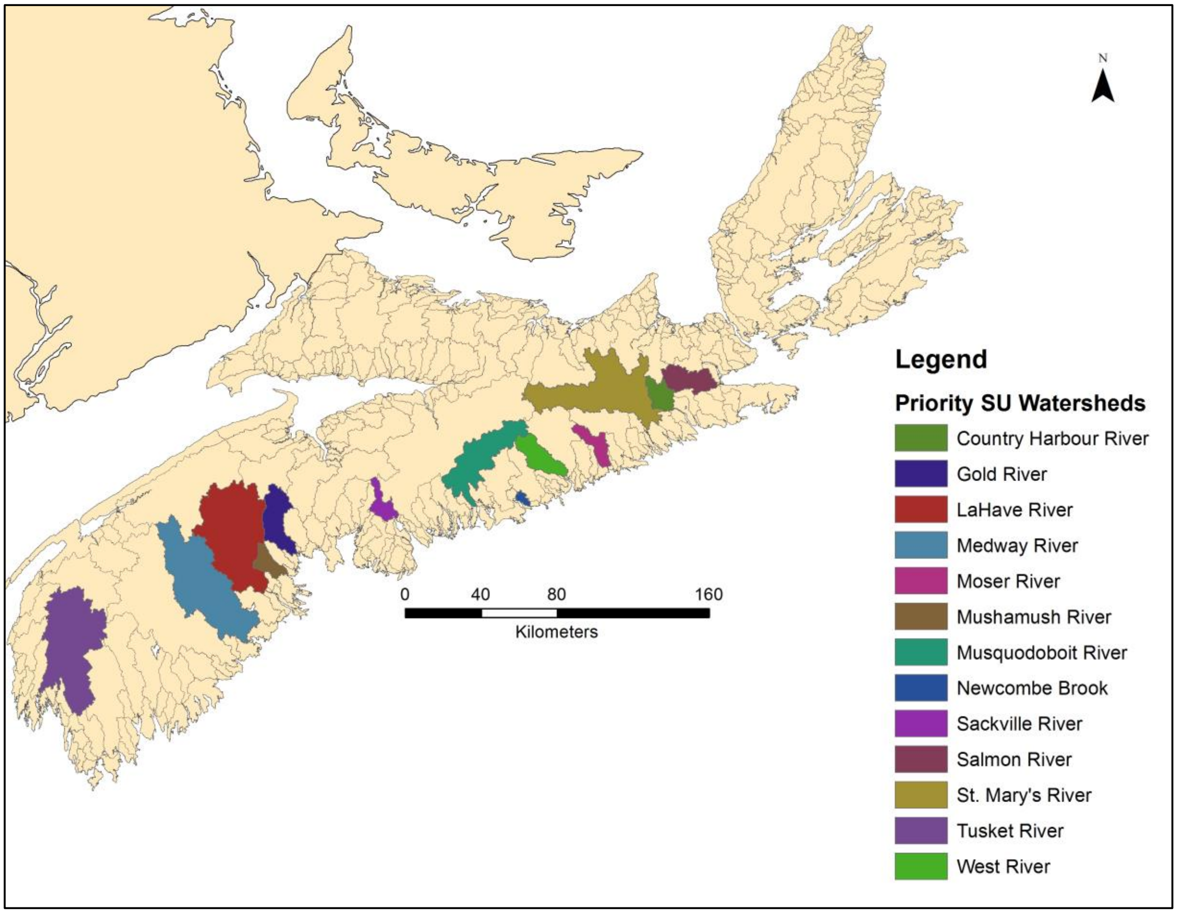


Figure 2. Map of the 13 priority watersheds in Nova Scotia, Canada. Map generated using ArcMap 10.1. Watershed layer is from Sterling et al. (2014-a).

3.2.2 Watershed delineation

To perform the analysis needed for this research I created a hydrological correct map of each of watersheds. Each of the 13 priority watersheds were delineated using ArcGIS 10.1 and ArcHydro tools. Methods for the delineation were developed through consultation with the Dalhousie GIS Help Centre and with Environmental Systems Research Institute (ESRI) support

(Merwade et al., 2006; Esri Water Resources Team, 2011). The data required for the watershed delineation include provincial flow line and provincial Digital Elevation Model (DEM). The provincial flow line and DEM with 20m resolution used in this study is from Sterling et al. (2014-b). The watershed delineation methods are available in Appendix 10.1.

Analysis of the 13 watersheds at a watershed level would involve generalizations which may compromise the accuracy of the results, therefore each watershed was divided into watershed units that are more manageable for analysis. For the purpose of this study watershed units are defined as the N-1 subbasins (N is the stream order of the watershed) and the residual (watershed area not included in the N-1 subbasins). I identified stream order and the N-1 subbasins by hand using methods outlined in the Coastal Watershed Assessment Procedure Guidebook (CWAP) Interior Watershed Assessment Procedure Guidebook (IWAP) by the British Columbia Ministry of Forests (B.C. Ministry of Forests, 2001). Once identified by hand I delineated each N-1 watershed using interactive pour point selection using ArcHydro point delineation (Merwade et al., 2006; Esri Water Resources Team, 2011; see Appendix 10.1). This resulted in each watershed having N-1 subbasins and residual watershed units which is the unit of the exclusionary criteria analysis. There are 44 watershed units within the 13 priority watersheds including 31 subbasins and 13 residuals.

3.3 Selection criteria

Using multiple selection criteria I have identified and prioritized catchments for terrestrial liming within the 13 priority watersheds. Although terrestrial liming would be more effective at decreasing the risk of SU extirpation when applied to an entire watershed, it would require an enormous amount of lime and helicopter application which is not feasible for terrestrial liming budgets at this time. Two sets of selection criteria are used: exclusionary and prioritization criteria. The selection criteria are used to identify and prioritize catchments that are support effective terrestrial liming and the SU population.

3.3.1 Selection of exclusionary criteria

Exclusionary criteria were selected based on attributes that best support water quality improvements with terrestrial liming and feasible liming application. The watershed units (N-1 subbasins and residuals) of the 13 priority watersheds are the unit of analysis for the exclusionary criteria. The exclusionary criteria are based on the assumptions that ground application methods will be used; this assumption is based on consultation with various stakeholders including community groups and scientists (i.e., DFO) and the Southern Upland Collaborative Projects Working Group. I have identified four criteria used to determine if a watershed unit or catchments within have potential to be limed, the catchment:

1. must be acidified
2. must not contain Acid Rock Drainage (ARD)
3. must not flow into a large lake
4. must be accessible by road

Watershed area that do not meet the exclusionary criteria will no longer be considered for terrestrial liming in this study (Figure 3).

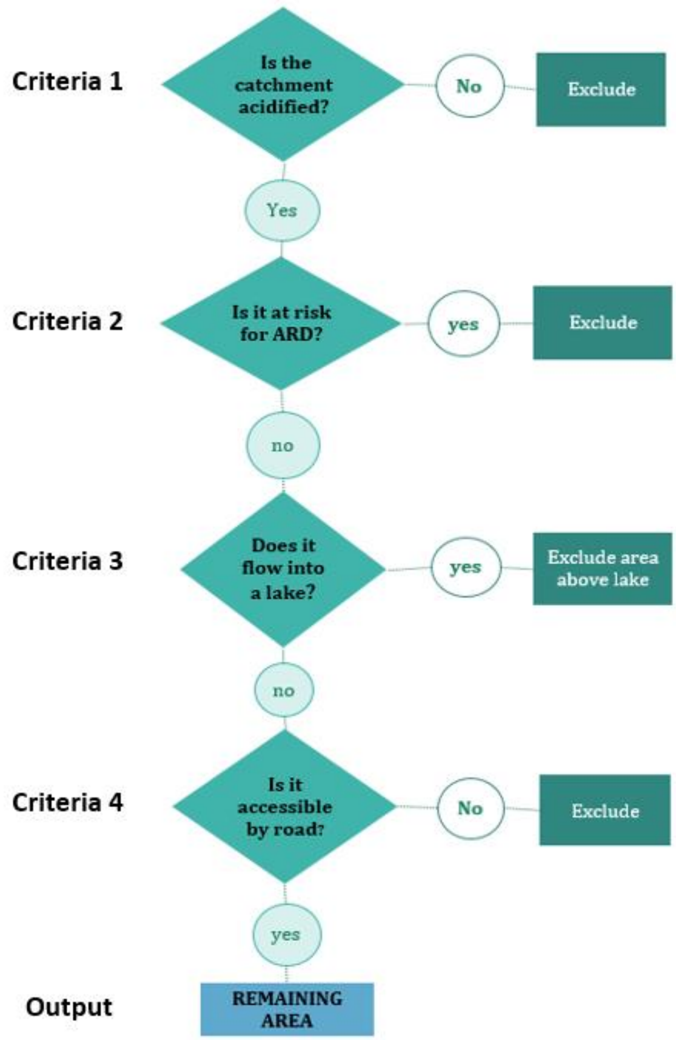


Figure 3. Flow chart representing the decision-making process involved with excluding watershed units or catchments based on the four exclusionary criteria.

I use four exclusionary criteria in the catchment prioritization model in order to identify watershed area that supports effective and feasible liming; each of these criteria are detailed below.

Exclusionary criterion 1: catchments must be acidified

Focusing on the most acidified watershed units within the 13 priority watersheds limits my study to the catchments that best meet the objective of decreasing risk of expiration for the SU salmon. Liming catchments that are not acidified will not improve water quality and therefore will not contribute to improving habitat quality for the SU salmon. The greatest risk of expiration for the SU salmon populations are within the most acidic catchments and therefore I have focused on reducing the probability of expiration in these catchments.

The most acidified watershed units were determined by calculating how acidic each watershed unit is and then excluding watershed units that are not acidic. Watershed units that are not acidic are those above a specified 'acidification threshold' value that I have set based on the spread of the data. There hasn't been a recent pH survey conducted in Nova Scotia (Watt et al., 1983) therefore I will use Acid Neutralizing Capacity (ANC), which represents a bedrock, soil and surface waters ability to neutralize or offset acidic inputs, as a proxy for how acidified a watershed unit is.

I used an acidification raster layer with a 250m resolution to calculate the mean ANC value for each watershed unit. The raster layer was created by Clair et al. (2007) based on water samples measured using the gran titration method (Gran, 1952). The gran titration method enables the measurement of the sum of carbonate buffering plus organic buffering, which is important to include in measurements of ANC in Nova Scotia because of the abundance of wetlands that produce organic acids (Clair et al., 2007). Clair et al., 2007 interpolated the ANC values from his samples to create the raster layer used for this project. I used ArcGIS zonal statistics methodology to calculate the mean ANC value for each watershed unit (Figure 4; see Appendix 10.2 for more details).

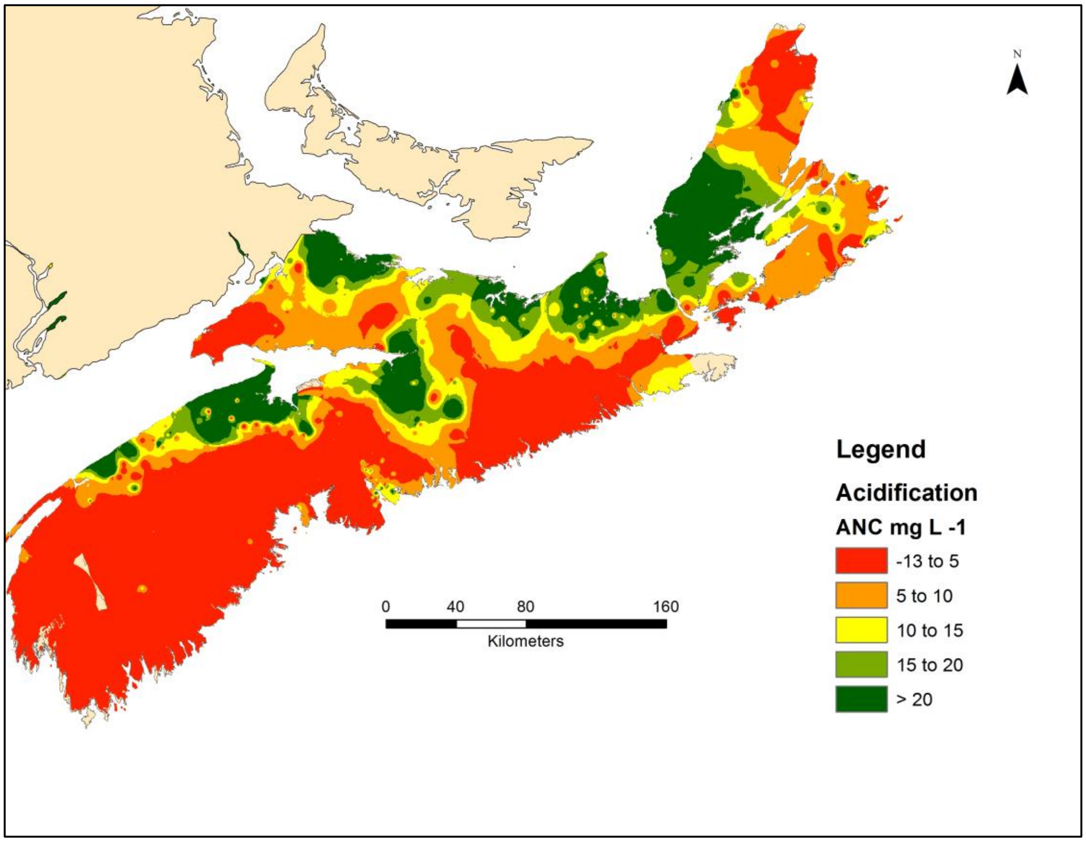


Figure 4. Map of the acidification raster layer based on Acid Neutralizing Capacity (ANC_G) values (Clair et al., 2007) for Nova Scotia, Canada.

The acidification threshold value is an ANC of 5 mg L^{-1}; I excluded watershed units with an ANC value greater than the threshold value. The threshold value was selected using an inclusionary approach aimed at ensuring all possible sites with potential priority catchments for liming are included. Although the spread of the ANC values for the watershed units indicates a natural break in the data at an ANC of 3 mg L^{-1}, taking an inclusionary approach, I increased the value to 5 mg L^{-1}.

Exclusionary criterion 2: catchment must not contain Acid Rock Drainage (ARD)

Acid Rock Drainage (ARD) occurs when rocks bearing sulphide minerals are exposed to water or air and oxidation occurs causing the leaching of sulfuric acid (EPA, 1994). ARD can acidify or further acidify a river or lake, therefore mitigating acidification in regions exposed to ARD is difficult. Liming an area exposed to ARD poses the risk of either not improving the water quality or improving the water quality temporarily until the sulphide bearing rock is disturbed causing ARD and re-acidification of the waters (Sterling et al., 2014-a). To avoid the risk of ARD in a liming project, it is best to exclude areas underlain with sulphide bearing rocks that are exposed to current human development that may disturb the rock and cause acid drainage.

ARD in SWNS is caused by the exposure of the Halifax formation of the Meguma Group which is bedrock formed of pyritic slate (Fox et al, 1997). To determine current exposure to ARD in Nova Scotia I created a GIS layer that represents area underlain by the Halifax Formation with surficial geology attributes making it vulnerable for exposure and where there is current human development (Figure 5, ARD area layer). I made the assumption that the ARD area layer represents true areas where ARD is currently occurring. The location of human development activities used to create the ARD area layer include quarry sites, human land use and roads; these areas are assumed to expose Halifax Formation rock to air or water thus causing ARD (see Appendix 10.3 for GIS methodology). The input layers used to create the ARD layer (Halifax formation and human development) are from Sterling et al., (2014-b).

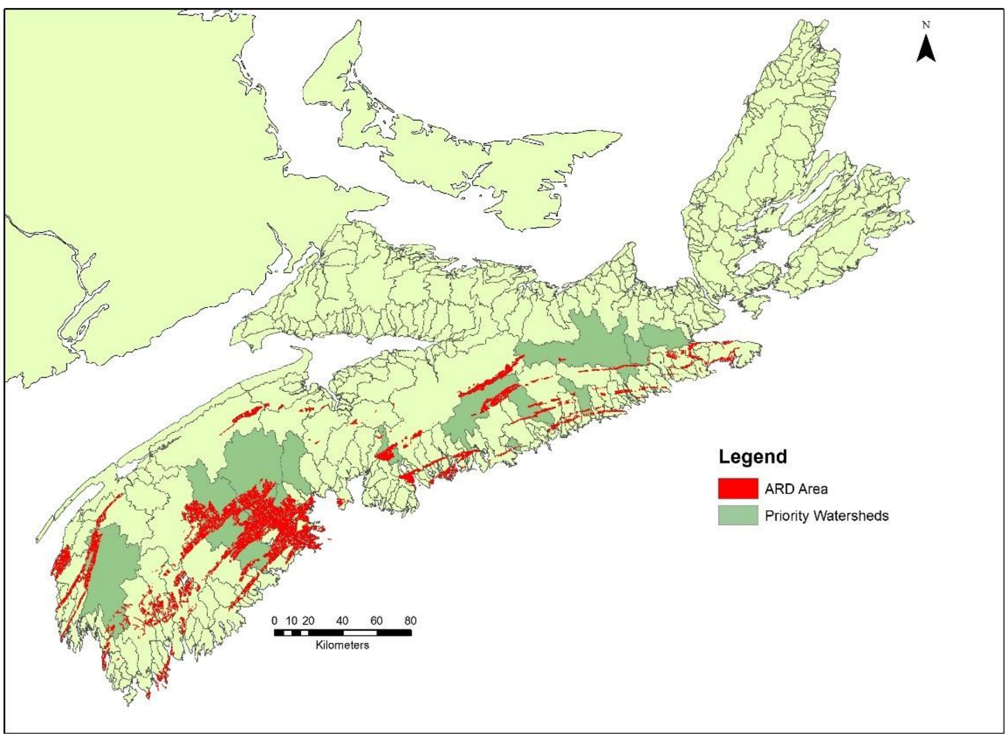


Figure 5. Map showing the area currently exposed to ARD in Nova Scotia, Canada. The area currently exposed to ARD in Nova Scotia is 1295.25 km^2. ARD input layers from Sterling et al. (2014-b).

The percentage of each watershed unit exposed to ARD was calculated by dividing the area of exposure within a watershed unit by the total area of the watershed unit then multiplying by 100 to give a percentage. This is represented in equation form below:

$$Ar\ (\%) = \frac{\text{ARD area of a watershed unit}}{\text{Watershed unit area}} \times 100 \qquad (1)$$

Ar (%) = the percentage of the watershed unit currently exposed to ARD.

I excluded watershed units that have greater than 5% area currently exposed to ARD; this ensures that remaining watershed units considered for terrestrial liming will not be exposed to large amounts of ARD.

Exclusionary criterion 3: must not flow into a large lake

I have excluded catchments that flow into large lakes based on the assumption that liming catchments that flow into large lakes will not affect or improve water chemistry downstream of the lake. The base cations used in terrestrial liming are high in calcium content, which is a primary nutrient for biota (Berner and Berner, 1987); this is relevant because lakes typically have higher productivity compared to rivers and therefore the lake biota will uptake the calcium from liming and little to no calcium will remain in the waters downstream. Another factor contributing to the uptake of calcium in lakes is the longer residence time, the average amount of time that a molecule spends in a water body (Berner and Berner, 1987), of lakes compared to rivers. The longer the calcium remains in the lake, the more it will be taken up by the lake biota. Terrestrial liming above large lakes with long residence time may not be effective at improving water quality downstream because the base cations will be taken up by the biota in the lake.

Catchments that flow into large lakes are excluded from my study because liming these catchments would not improve water quality downstream. I have defined a ‘large’ lake as a lake with an area greater than 100,000 m^2; excluding areas above only large lakes insures that only the catchments that drain into lakes that are do not support improving water quality downstream are removed from the study. Unfortunately there are no available data on the residence time of Nova

Scotia lakes and therefore lake area is used as a proxy for lake size and residence time. The lake layer from Sterling et al., (2014-b) is used for the analysis. I identify excluded areas that drain into large lakes using an interactive pour point delineation method in ArcHydro (see Appendix 10.1). I used an inclusionary methodology for the lake exclusions and therefore did not exclude catchments that drain into lakes less than 1% of the catchment size; this is based on the assumption that the biota in these lakes would be unable to uptake all the base cations from upstream terrestrial liming. The one exception to this rule is the top priority site identified by the MTRI (2010) study within the Gold River watershed. Although the MTRI site drains into a large lake (320,426 m^2) it was included in the study to ensure that decision makers can make the most informed choices regarding terrestrial liming within the Gold River watershed.

Exclusionary criterion 4: must be accessible by road

The two types of application methods used in terrestrial liming are helicopter and ground applications. Although studies from Europe have shown using helicopter application is more effective (Yan et al., 1995; Hindar et al., 2003), after consultation with community groups at the Southern Upland Collaborative Projects Working Group, I have determined that ground application is the only viable method in Nova Scotia at this point in time due to budgetary constraints. The road accessibility is important for terrestrial liming application because the lime will have to be delivered by dump truck and is likely involve the use of off-road vehicle and distributing the lime by hand throughout the catchment. Ground application methods were used in Sterling et al., (2014-a) to apply the lime throughout the Maria Brook catchment; although this site had good accessibility with a road nearby and a trail throughout the catchment it was still very labour intensive, highlighting the importance of good accessibility in a liming site.

I excluded catchments that are inaccessible for ground application; an inaccessible catchment is defined as a catchment that's perimeter does not intersect with a road or trail. I only excluded catchments that were off of the N, N-1, or N-2 watersheds (N stands for stream order) because this reduces the probability of excluding smaller catchments that fall within a larger catchment that may be a good candidate for terrestrial liming. The road layer from Sterling et al. (2014-b) is used for this assessment. An interactive point delineation method will be used for the catchment delineation (see Appendix 10.1).

3.3.2 Identifying catchments

The next step following the exclusions was to identify catchments within the remaining (non-excluded) area within the 13 priority watersheds. This involved calculating the amount of critical habitat necessary for a set population of SU salmon at a set egg area requirement (eggs/m^2). The calculation to determine the amount involves the use of multiple SU population parameters (figure 6). Population parameters of two types were used: first those that determine the number of eggs that a set population will produce, which will remain constant, and second the parameters which determine the set population and egg area requirement, these parameters can change depending on the assumptions for area requirements and project objectives.

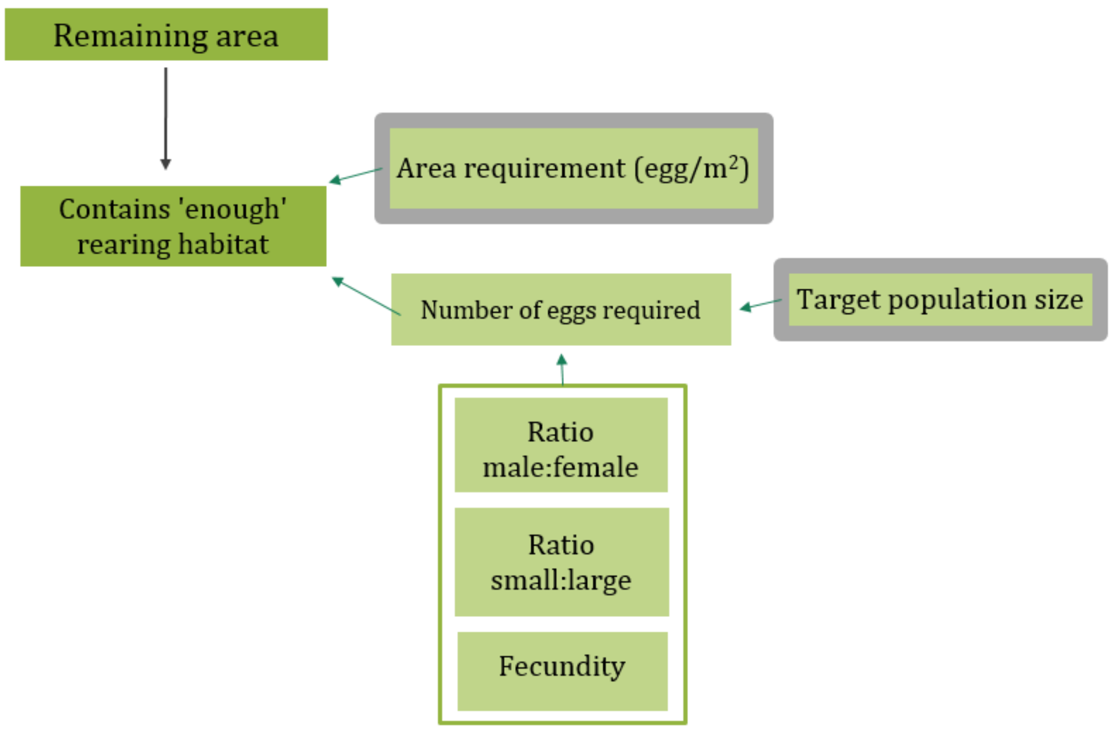


Figure 6. Flow chart showing the population parameters used to calculate amount of rearing habitat for a set target population. The three population parameters within the green box are calculated based on the LaHave River population and will remain constant; values were determined through consultation with DFO.

The first type of population parameters determine the number of eggs that a set population will produce and include three parameters: the ratio of small (one sea-wintering salmon) to large (multi sea-wintering salmon); the ratio of male to female for small and large salmon and; the fecundity (number of eggs produced) for small and large salmon. The values for the three population parameters will remain constant throughout the study. The LaHave river population will be used as an index population for the SU salmon, a method also used by DFO when assessing the SU population. I calculated the ratio of small to large salmon using LaHave River population data from the last 15 years provided by DFO. The mean ratio of male to female and fecundity was determined through consultation with DFO. The mean values for population parameters are:

- Ratio of small: large salmon = 0.77 : 0.23
- Ratio of male: female
  - for small salmon = 0.543 : 0.457
  - for large salmon = 0.083 : 0.917
- Mean fecundity (eggs/female)
  - for small salmon = 3,195 eggs
  - for large salmon = 6,310 eggs

The second type of population parameters used to determine the minimum rearing area that a catchment must have are those that change according to a projects assumptions, objectives and budget. These parameters include the area requirement per egg and the target population size for each catchment. I have selected an area requirement of 2.4 eggs/m^2 which remained constant throughout the study. A 2.4 eggs/m^2 area requirement is identified as the Atlantic salmon conservation requirement by DFO (Gibson and Claytor, 2013). To deal with the uncertainty and variation of these parameters among different liming projects, I have developed multiple scenarios based on a range of different target population sizes.

I use three scenarios that vary only based on target population size: scenario one with a target population size of eight salmon, scenario two with a target population size of 15 salmon and scenario three with a target population size of 30 salmon. The target population sizes were selected to ensure that there was a good spread between the area requirements for each scenario and that the catchments identified contain enough critical salmon habitat to support the target number of SU salmon.

The calculation to determine the required critical habitat area includes five population parameters: ratios of small to large and male to female, fecundity, egg area requirement and target population size (figure 6). There are three major steps involved in calculating the critical area requirement at a set egg area requirement and target population size: determining the amount of small and large salmon in the LaHave river index population, calculating the amount of eggs produced by the target population size and calculating the suitable area required for the number of eggs produced; each step is described in detail in Appendix 10.5.

The stream width used in the river area calculation for each watershed was calculated using results from the orthophoto analysis described in Amiro (1993). The stream width data was provided by DFO who have requested that I do not publish the raw data or calculations. The stream widths, among other attributes, were provided for subcatchments within all watersheds units remaining after the exclusionary analysis which includes Country Harbour, Gold, LaHave, Moser, Mushamush, Sackville, Salmon River, St. Mary's, West and Tusket River Watersheds. The quality of the data varied among the watersheds with some watersheds having many catchments sampled and some having very little. I found the Tusket River data file was not consistent with the other watershed files; stream widths for the Tusket River catchment averaged at 0.89 meters whereas other large catchments such as the LaHave River had a much larger average of 19.77 meters. I decided, because this variation between files seems out of the range of normal, to instead use the averages from the other eight watersheds as the average stream width for the Tusket River.

The critical habitat for the SU salmon consist of a riffle-pool-riffle sequence. The salmon build redds (spawning gravels) within the rearing habitat containing coarse gravel and cobble with a median grain size between 15 and 30mm (Bowlby et al., 2014). The riffle-pool-riffle sequence typically develops in streams with a stream gradient of 0.12% - 5% (DFO, 2013; Bowlby et al., 2014). There has not been a critical habitat survey for the SU salmon population and there is no data on the locations of riffle-pool-riffle sequences with the proper gravel and cobble are within my study area therefore used a stream gradient of 0.12% - 5% as a proxy for rearing habitat for my study. I calculated stream length within a catchment that has a stream gradient between 0.12 - 5% and identified catchments that contain a stream length equal to or greater than the required stream length for the target population for each scenario.

3.3.3 Selection of prioritization criteria

The identified catchments were assessed based on prioritization criteria that support effective liming and support the SU salmon population. The terrestrial liming catchment prioritization model uses four prioritization criteria that meet the goal of assessing a catchments suitability for liming and supporting the SU salmon population: connectivity, accessibility, ARD risk, land ownership and consideration for invasive species distributions between watersheds. I used the results from the prioritization analysis to score and identify the top priority catchments for terrestrial liming. The prioritization criteria are described below.

Prioritization criterion 1: connectivity

For the purpose of this study I adopted the definition of connectivity used by Toms et al., (2010) in the MTRI report on selecting terrestrial liming sites within the Gold, LaHave and Medway Watersheds; distance from the mouth of the catchment site to the mouth of the primary watershed following the most direct route along the main river. Although there are other definitions of connectivity (Bracken et al., 2013), this definition allowed the assessment of the distance that the salmon must travel on the main river to enter the limed catchment.

Each catchment has a calculated connectivity distance value representing the distance from the mouth of the catchment to the mouth of the main river into the Atlantic Ocean. I used the connectivity distance to score the catchments from highest priority (least distance to the mouth of the main river) to lowest priority (greatest distance to the mouth of the main river).

Prioritization criterion 2: accessibility

This study is assuming ground application methods will be used for terrestrial liming in Nova Scotia based on stakeholder consultation. The accessibility of a catchment for terrestrial liming is measured as the length of road within a catchment site. Catchments that are more accessible will have more roads within their catchment; this will make terrestrial liming less labour intensive and expensive. The accessibility value for each catchment will be the length of road within each catchment normalized by the area of the catchment. The accessibility is used to score the catchments from highest priority (greatest proportion of road within the catchment) to lowest priority (lowest proportion of road within the catchment).

Prioritization criterion 3: Acid Rock Drainage risk

Acid Rock Drainage (ARD) in SWNS is caused when the Halifax Formation rock formation is exposed to air or water and produces sulfuric acid, as described in section 3.3.1. The exclusionary selection criteria considers current ARD where area of the Halifax Formation is exposed to air or water through current human development. Alternatively the assessment of ARD risk as a prioritization criterion considers the location of the Halifax formation alone. The ARD risk calculation identifies areas that are at risk for ARD if development were to occur in the future.

The ARD risk is calculated and measured similarly to the ARD exclusionary criteria but will only consider the Halifax Formation (see section 3.3.1). The catchment area underlain by the Halifax Formation is calculated and given as a percentage of the catchment. The ARD potential percentages is used to score the catchments from highest priority (lowest ARD potential percentage) to lowest priority (highest ARD potential percentage).

Prioritization criterion 4: land ownership

Land ownership is an important consideration when prioritizing catchments to lime. Terrestrial liming ground application is labor intensive and requires dump truck accessibility and labourers moving throughout the catchment. From stakeholder consultation I have gathered that it is difficult to gain permission for terrestrial liming from private landowners and that land owned by crown or corporations (i.e. forestry companies) are more likely to grant access for terrestrial liming.

Using the Nova Scotia Civic Addressing File (NSCAF) layer I have calculated the percentage of each catchment that is privately owned. I acquired the NSCAF layer from the Dalhousie GIS Help Centre with the private ownership information removed; the removal of the private land owner’s information allowed the easy identification of the privately owned areas. I scored catchments with the lowest proportion of privately owned land as highest priority with the lowest priority assigned to catchments with the highest proportion of privately owned land.

Invasive Species Distribution Considerations

The two invasive fish species that compete with the SU salmon in SWNS are Chain Pickerel (*Esox niger*) and Small Mouth Bass (*Micropterus dolomieu*). Although it would be most informative to determine the presence or absence of invasive species within each catchment, due to data limitations, this is not possible. The most complete database containing distribution data for Chain Pickerel and Small Mouth Bass distribution in Nova Scotia is from DFO. Unfortunately this layer is outdated (last updated in 2011), does not contain many data points and lacks information regarding the source of the species observation. Unfortunately this data is not reliable and accurate enough to conduct a catchment level invasive species distribution assessment with a high level of certainty.

I will conduct a watershed level assessment on the distribution of invasive species for the 13 priority watersheds. Although invasive species distributions will not be considered to prioritize catchments for the purpose of this thesis, it can provide more information to decision makers when deciding between watersheds and identifies the need for more accurate and reliable invasive species distribution data. I will provide information on the presence and absence of Chain Pickerel and Small Mouth Bass within each of the 13 priority watersheds by creating a GIS layer from the invasive species distribution excel file from DFO and visually assessing the distributions.

3.4 Catchment site scoring

Each catchment was scored based on the prioritization criteria described in section 3.3.3. The catchments within each watershed were scored independently (i.e., only catchments within the Gold River Watershed will be scored and prioritized against each other) using a weighted scoring scheme similar to the MTRI (2010) report (Toms et al., 2010). The weighted scoring scheme is designed to give criteria that have a greater influence on the effectiveness of liming, that best support the SU salmon and that have more reliable data, a greater influence on the results.

The greatest weight is assigned to connectivity and accessibility because these two criteria are the most important for supporting the SU salmon and feasible liming application and also have reliable and available data. ARD potential is given a lower weight because current ARD is already assessed as an exclusionary criterion and will only be a factor for liming if future development occurs. The private land ownership criterion is least weighted because it is not certain that all private land owners will not permit access for terrestrial liming.

Table 3. Site scoring method with measurement, score value and description for each accessibility, connectivity and ARD potential criteria.

Criteria	Measurement	Score	Scoring description	Data used
Accessibility	Accessibility value (AV) = (Length of road/area of site) *100	Scored in increments of 10	Catchments are scored according to their AV with the highest AV value given an accessibility score of 0 and the lowest AV value given an accessibility score of 10(n-1), with n being the number of catchments being assessed.	Nova Scotia provincial road layer
Connectivity	Stream distance to ocean outlet following most direct route	Scored in increments of 10	Catchments are scored according to their associated stream length with the lowest stream length given an accessibility score of 0 and the highest stream length given an accessibility score of 10(n-1), with n being the number of catchments being assessed.	Nova Scotia provincial flow network and provincial DEM
ARD Potential	(Underlying ARD area/area of site) *100 = %	Scored in increments of 5	Catchments are scored according to the percentage ARD with the catchment with the lowest proportion ARD given a scoring value of 0 and the greatest proportion give an score of 5(n-1)	Halifax formation layer from Sterling et al. (2014-b)**
Land ownership	Percentage of privately owned land	Scored in increments of 2.5	Catchments are scored according to the percentage of catchment privately owned with the lowest privately own catchments given a score of 0 and the greatest percentage given a score of 2.5(n-1)	Nova Scotia Civic Addressing File layer with private names removed.

3.5 Stakeholder and expert consultation

Stakeholder and expert consultation was crucial for the development of my methods. Although the MTRI report (Toms et al., 2010) serves as a good baseline study to refer to, it does not include enough detail and is not comprehensive enough to enable it as the sole study to base my methods on. Stakeholder and expert consultation was used to gain local knowledge to aid in the development of my methods. Stakeholder and expert consultation was important for the identification of the selection criteria that support effective and feasible liming and the SU salmon population. Consultation with community groups, such as the Bluenose Coastal Action

Foundation, helped to identify catchment attributes important for feasible terrestrial liming; community groups will be taking on the responsibility for terrestrial liming projects and therefore their input was highly valued. Experts, such as fish biologists at DFO, helped to identify catchment attributes that support the SU salmon and contributed greatly to the development of catchment identification methods using the SU population parameters. There are no peer-reviewed research on site selection methods for terrestrial liming, therefore consultation with stakeholders was key to development of the catchment prioritization model.

3.6 Limitations and delimitations

There are some major limitations to this study because it is one of the first of its kind. A methodology for identifying or prioritizing terrestrial liming sites does not currently exist and therefore developing the methods for this study is difficult and time consuming. In addition there is a lack of data availability for important criteria for terrestrial liming such as recent pH data for Nova Scotia, SU critical habitat locations and updated invasive species distribution data. I have overcome these limitations by using indices for data that is unavailable (i.e., ANC for pH and stream gradient for critical habitat) and by clearly stating my assumptions (table 4).

Table 4. Summary of the assumptions of the model and potential impacts they may have on the results.

Assumption	Potential impact on results
Assumptions involving selection criteria	
The ANC interpolated layer well represents true acidification status	Used ANC values to exclude watershed units that are least acidified; potential to have falsely included or excluded watershed units.
Salmon preferentially select catchments	Excluded catchments draining into large lakes based on assumption that salmon preferentially select which catchment to spawn in based on water chemistry; potential to have excluded terrestrial liming sites
Private land owners are less likely to allow access compared to others (i.e., crown, forestry companies).	Catchments with lower proportion of privately owned land is given higher priority; because this prioritization criteria has a low weight, this assumption has a small impact on the results.
Connectivity and accessibility are two times more important than ARD risk and four times more than land ownership in supporting effective liming and the SU salmon	The weights of the prioritization criteria have direct influence over the results and determine which catchments are of higher or lower priority; potential incorrectly prioritized the catchments due to improper weighting.

Assumptions involving catchment identification	
2.4 eggs/m^2 egg area requirement (Gibson, 2013)	Number used in calculating the spawning area required per female; directly affects the estimate of the number of salmon that can spawn in a catchment – could overshoot (more area then required) or undershoot (not enough area).
LaHave River population is representative of the entire population	Key population parameters were calculated based on the LaHave population which directly relates to the number of eggs produced by each female and therefore the area requirement—potential to miscalculate area.
Stream width assumption (Amiro., 1993)	The width measurement directly influences the stream length requirement for a catchment; potential to miscalculate the stream length requirement and overshoot (too much spawning area) or undershoot (not enough spawning area) for a target population.
Spawning area (riffle-pool-riffle sequence) forms in rivers with a slope of 0.12-5%	The slope required for spawning area was used to identify the critical area of a catchment; this directly influenced the identification of catchments—potential to have misclassified areas as critical or none critical.
All river area with a slope of 0.12-5% or 0% are spawning areas. Assumed 0% slope represents a raster calculation error.	All stream within or equal to the said slopes are critical areas. Potential to misclassify river area as critical.

The study is delimited by the study area, selection criteria and population parameter assumptions for the SU salmon. The study area for this project would ideally involve all watersheds within the SU salmon range but I delimited my study to the 13 priority watersheds due to limited time and the fact that an improvement in water quality within these watersheds would best support the SU salmon. I selected four exclusionary and four prioritization criteria based on attributes that will best support effective liming and the SU salmon population. I also delimited my selection of catchments based on assumptions of population parameters and stream attributes.

5.0 Results

The results of the exclusionary and prioritization analysis are given in addition to the detailed results from the catchment prioritization model. The results for the exclusionary analysis include the watershed units and values that are the basis for exclusion. The results from the prioritization analysis for the remaining watershed units will be described in tabular form with the site scoring results described in both map and tabular forms; this provides a clear description of the top priority sites for terrestrial liming in Nova Scotia. In addition I have identified the key information needs required for improved terrestrial liming catchment selection.

5.1 Exclusion results

The study area is composed of 44 watershed units (31 N-1 subbasins and 13 residuals) within the 13 priority watersheds. The watershed units are the level of analysis for exclusionary criterion one and two (catchments must be acidified and must not contain ARD, respectively). Watershed units were assessed based on the exclusionary criterion and units that did not meet the criteria requirement defined in this study were excluded. I excluded 20 watershed units with the exclusionary criterion one and two assessments.

Catchments within the remaining watershed units were assessed for exclusionary criterion three and four (catchments must be accessible and must not drain into large lakes, respectively). This did not typically result in exclusions of entire watershed units but of smaller catchments within the units. The exception to this is Newcombe Brook and Mushamush watersheds who had entire watershed units excluded because of low accessibility or a high proportion of large lakes; this is described in section 5.1.3.

5.1.1 Exclusionary criterion one: catchments must be acidified

The catchments must be acidified in order for terrestrial liming to improve water chemistry and salmon habitat therefore I excluded the least acidified watershed units from my study. I calculated average ANC values for each of the 44 watershed units (N-1 subbasins and residuals) and excluded units with an ANC value greater than 5 mg L^{-1}. This resulted in the exclusion of nine watershed units with ANC values ranging from 5.04 mg L^{-1} (St. Mary’s River subbasin A) to 15.10 mg L^{-1} (Musquodobit subbasin A). See table 5 for ANC values for all excluded watershed units.

Table 5 Average ANC values for excluded subbasins (SB) and residuals listed in alphabetical order. Average ANC values calculated using ArcGIS 10.1 and an ANC layer by Clair et al., 2007.

Watershed unit name	**ANC Value (mg L^{-1})**
Country Harbour SB B	6.93
Country Harbour SB C	5.30
Musquodobit SB A	15.10
Musquodobit SB B	9.98
Musquodobit residual	9.51
Salmon River SB A	5.64
Salmon River SB B	5.34
St. Mary's SB A	5.04
St. Mary's SB B	9.41

5.1.2 Exclusionary criterion two: catchments must not contain ARD

Liming catchments must not be exposed to large amounts of ARD because it further complicated the acidification issue by adding additional acidic inputs into a river and thereby decreasing the effectiveness of terrestrial liming. I excluded watershed units which have greater than 5% area currently exposed to ARD. There are 12 watershed units with current ARD exposures ranging from 6.05% (West River subbasin B) to 36.28% (Mushamush subbasin A) that were excluded from the study. See table 6 for the percentages exposed to ARD for the excluded watershed units.

Table 6 Proportion of area currently exposed to greater than five percent ARD for each excluded watershed. Proportion of area exposed to ARD was calculated using ArcMap 10.1 and layers from Sterling et al. (2014-b). Watershed units are listed in alphabetical order.

Watershed unit name	**ARD exposed area percentage (%)**
LaHave residual	32.16
Medway SB A	8.91
Medway SB B	13.89
Medway residual	12.59
Mushamush SB A	36.28
Mushamush SB B	10.31
Mushamush residual	29.38
Musquodobit SB A	10.01
Sackville SB A	15.21
Sackville residual	25.38
Tusket SB A	10.52
West River SB B	6.05

5.1.3 Exclusionary Criteria three and four: must be accessible and not drain into a lake

The catchments must be accessible by roads and trails for ground application therefore I excluded catchments which have no roads or trails located within its area. The catchments must not drain into a large lake to ensure terrestrial liming is effective at improving water chemistry downstream therefore I excluded catchments which drain into large lakes (100,000m^2). The 24 watershed units that were not excluded during the acidification and ARD analysis (criterion 1 and 2, respectively) are from nine remaining watersheds (critical liming watersheds) and are listed with their associated ANC and current ARD exposure values.

Table 7 Remaining non-excluded watershed units (n=24) following acidification and ARD analysis exclusionary analysis. Remaining watershed units have an ANC value less than 5 mg L^{-1} and are exposed to less than 5% ARD. Watershed units are listed in alphabetical order.

Watershed unit name	ANC (mg L^{-1})	ARD (%)
Country Harbour SB A	4.4871	0.7778
Country Harbour residual	4.4385	2.3373
Gold SB A	0.9985	0
Gold SB B	1.6031	0
Gold SB C	1.2367	0
Gold residual	0.7496	0
LaHave SB A	2.3595	4.1254
LaHave SB B	1.3730	4.4308
Moser SB A	1.2156	1.8603
Moser SB B	0.5181	0
Moser residual	0.6554	3.0166
Mushamush SB C	0.9272	2.4078
NewBrk SB A	1.1252	0
NewBrk SB B	0.8452	0
NewBrk SB C	0.6903	0
NewBrk SB D	0.6919	0.7752
Newcombe Brk. Residual	0.8469	2.7798
Sackville SB B	-0.0758	1.0893
Salmon River residual	3.9022	0
St. Mary's residual	2.7873	3.7637
Tusket SB B	0.1623	0.8178
Tusket residual	1.6535	0
West River SB A	0.1943	3.8556
West River residual	0.8021	1.3219

The 24 watershed units listed in table 6 are the units of assessment for the accessibility and lake exclusionary criteria. The watershed units contain catchments that I have excluded from the study because they drain into a large lake and/or were inaccessible by road (see section 3.3.1). The exception to this is Newcombe Brook and Mushamush river watersheds which I excluded from the study. I excluded all watershed units within the Newcombe Brook watershed because all units have extremely low accessibility (figure 7). I excluded the remaining watershed unit (subbasin C) within the Mushamush watershed because of the high abundance of large lakes in the watershed and at the mouth of subbasin C (figure 8).

Figure 7 Map of Newcombe Brook watershed showing the low accessibility identified by the absence of road polylines within the majority of the watershed. Map generated using ArcMap 10.1.

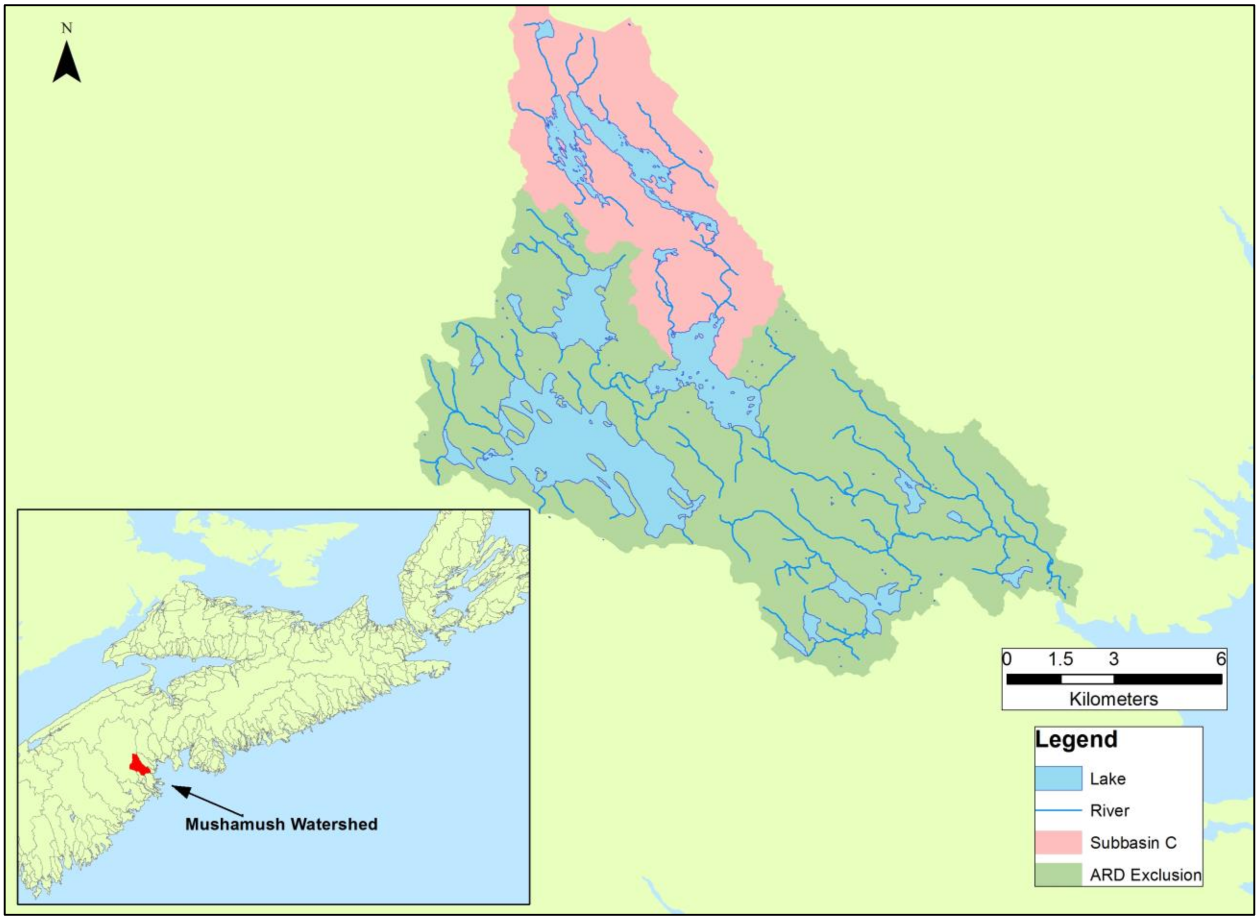


Figure 8 Map of the Mushamush river watershed showing the abundance of lakes within the watershed and at the mouth of subbasin C. Map developed using ArcMap 10.1.

5.2. Catchments Identified

Potential liming catchments were identified within the watershed units that were not excluded during the exclusionary analysis. Catchments were identified under three different scenarios based on a target population size of eight, 15 and 30 SU salmon. Catchments are identified within each of the nine remaining watersheds. The top site identified by MTRI (2010) within the Gold River watershed was identified and included. Table 8 describes the number of catchments identified within the remaining watersheds.

Table 8 Number of catchments identified within each watershed under 3 different scenarios (target population of 8, 15 and 30).

Watershed Name	Target Population Size			Total
	8	15	30	
Country Harbour	1	3	1	**5**
Gold River	1	5	1*	**7**
LaHave River	5	8	2	**15**
Moser River	1	2	1	**4**
Sackville River	0	2	1	**3**
Salmon River	3	2	0	**5**
St. Mary's River	3	0	0	**3**
Tusket River	6	8	2	**16**
West River	0	1	0	**1**

*Catchment identified by MTRI (2010)

5.3. Prioritization Results

There are 22 watershed units within nine watersheds that were not excluded from the exclusionary analysis. All catchments within each watershed are subject to the prioritization analysis and are scored amongst themselves based on the prioritization results. The top priority catchments for each of the nine watershed are identified through site scoring methods.

The four prioritization criteria used to score and prioritize catchments within each watershed are:

1. Catchments that are more accessible are of higher priority
2. Catchments that have higher connectivity (located closer to the mouth of the main river) are of higher priority
3. Catchments that are subject to less ARD are of higher priority
4. Catchments with a lower proportion of land privately owned are of highest priority.

The prioritization criteria is described in more detail in section 3.4, table 3. This results section will include the results from the prioritization analysis and site scoring for each watershed in table and map form.

5.3.1 Country Harbour Watershed

The Country Harbour watershed subbasins B and C were excluded from the study for having high ANC values (6.93 mg L^{-1} and 5.30 mg L^{-1}, respectively). Five sites were identified within the remaining subbasin A and the residual. The prioritization and site scoring results for the five catchments are given in table 9 and figure 9). Catchment B-15 is the top priority site having the greatest road density (accessibility), no ARD risk and relatively high connectivity. Catchment B-15 has a large proportion of area privately owned (71.86%) which needs to be addressed during the planning phase of terrestrial liming.

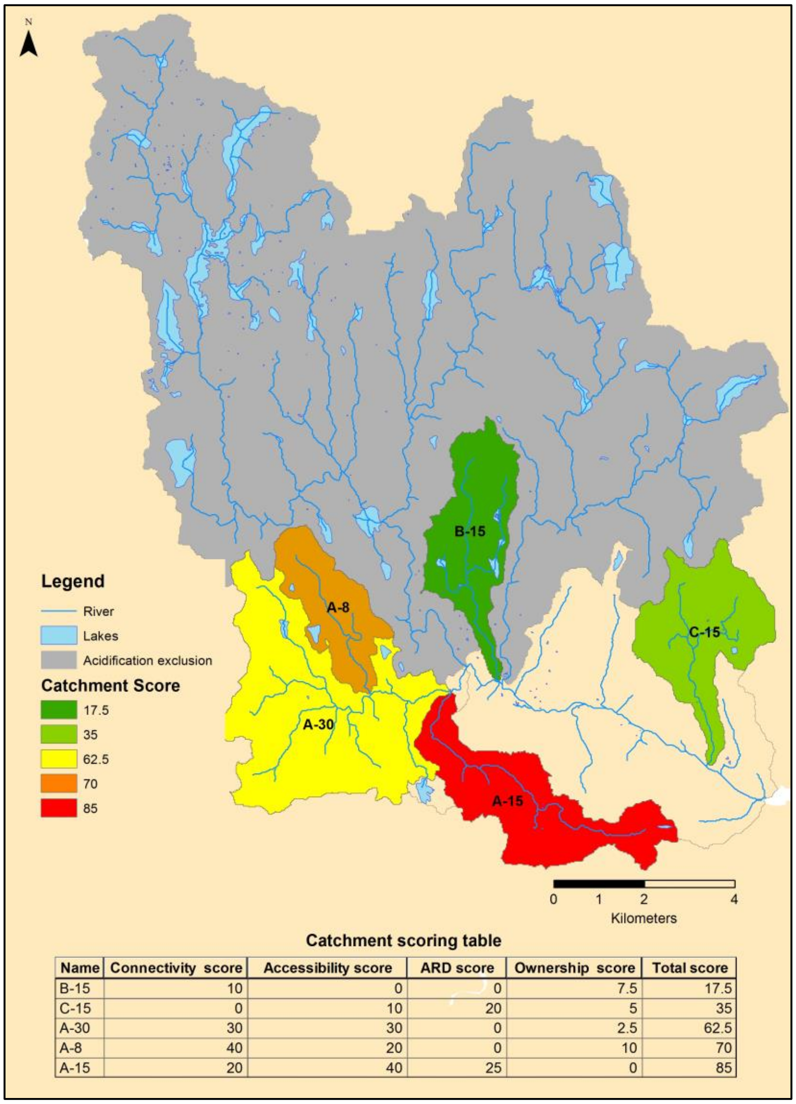


Figure 9 Scored catchments within Country Harbour watershed, Nova Scotia with the associated scoring table showing connectivity, accessibility, ARD (risk) and ownership (private) scores. The lower scores are of higher priority.

Table 9 Prioritization criterion values for catchments within Country Harbour watershed, Nova Scotia. Sites are listed from highest to least priority.

Name	Area (m^2)	Road Length (m)	Accessibility value	Connectivity length (m)	ARD risk (%)	Privately owned (%)
B-15	6494400	23363.07	0.3597	7275.78	0.00	71.86
C-15	7317600	19510.89	0.2666	1614.80	12.31	48.04
A-30	19778800	38995.98	0.1972	9258.86	0.00	42.46
A-8	4598800	11276.73	0.2452	11378.52	0.00	85.98
A-15	8163600	8091.58	0.0991	9258.86	14.09	24.71

5.3.2 Gold River Watershed

There were no watershed units within the Gold River watershed that were excluded during the exclusionary analysis. I identified seven catchments within the watershed, with one of these catchments being the top priority sites identified by MTRI (2010). There is no risk for ARD within the Gold River watershed because the Halifax Formation (bedrock of pyritic slate) does not underlay the catchments. The prioritization and site scoring results for the five catchments are given in table 10 and figure 10). Catchment A-15 is the top priority site with the highest connectivity and second highest accessibility. It is important to note that catchment A-15 has the greatest proportion privately owned (86.37%) and that decision-makers should address this in the early stages of terrestrial liming planning by speaking with these land owners.

Catchment A-8 was measured for aluminum concentrations during an aluminum survey of the Gold River watershed by the Dalhousie Hydrology lab in the summer of 2014. Results from the aluminum study showed that aluminum concentrations within the Gold River watershed often exceed the aluminum toxicity threshold of 15 ug L^{-1} and that catchment A-8 was found to have Ali concentrations between 80 and 210 ug L^{-1}; this needs to be taken into consideration by decision makers prior to terrestrial liming application.

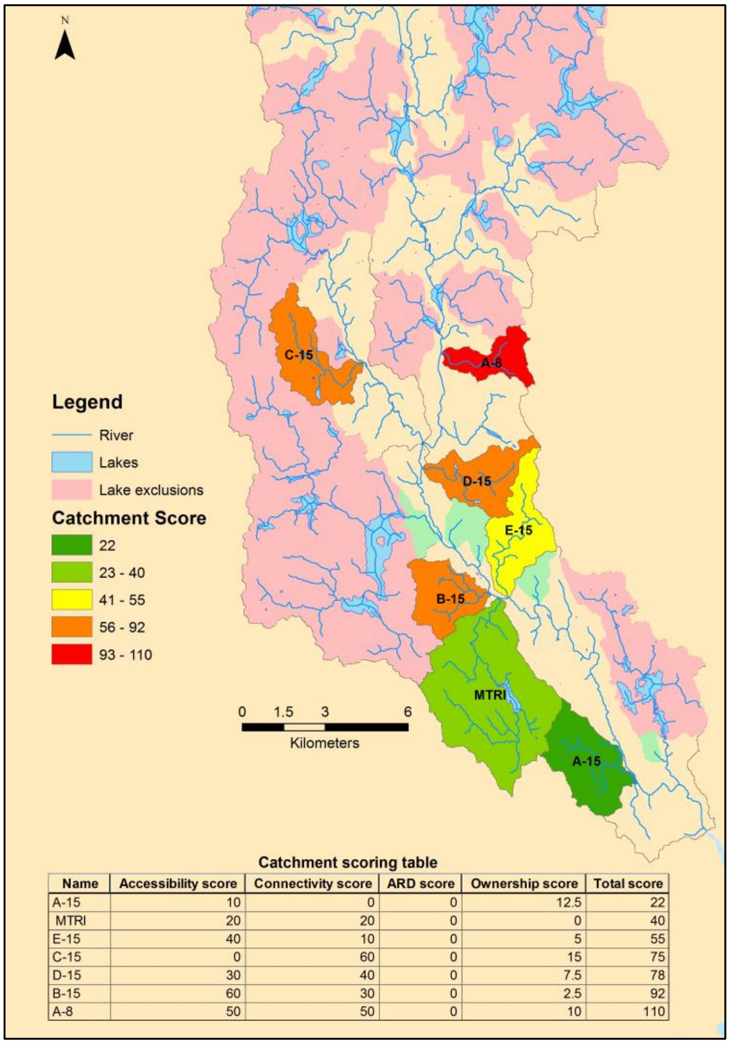


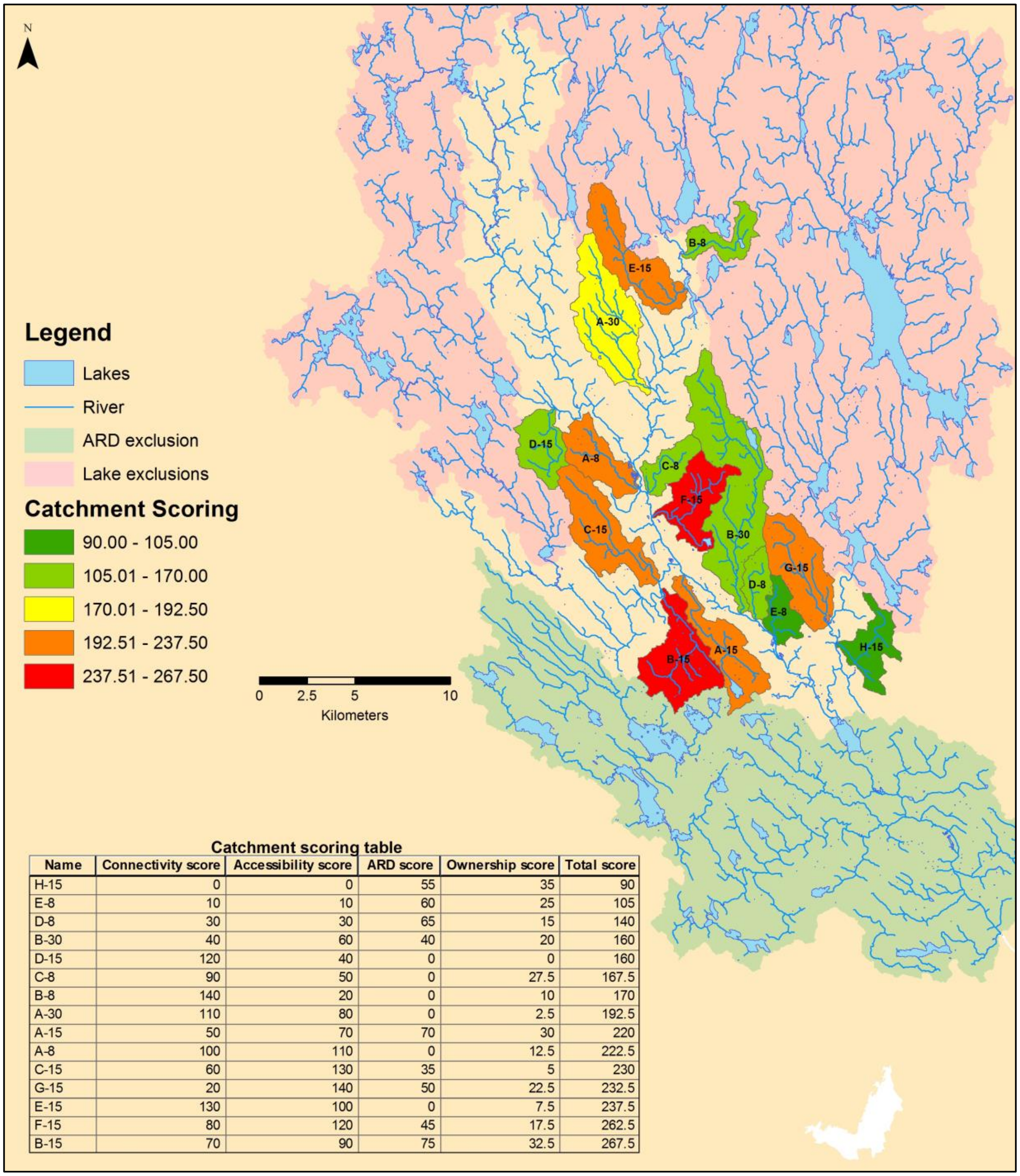
Figure 10 Scored catchments within the Gold River watershed, Nova Scotia with the associated scoring table showing connectivity, accessibility, ARD (risk) and ownership (private) scores. The lower scores are of higher priority.

Table 10 Prioritization criterion values for catchments within the Gold River watershed, Nova Scotia. Sites are listed from highest to least priority.

Name	Area (m^2)	Road Length (m)	Accessibility value	Connectivity Length (m)	ARD risk (%)	Privately owned (%)
A-15	7382800	13764.80	0.1864	4597.72	0.00	86.37
MTRI	20046400	27298.00	0.1362	16508.54	0.00	28.43
E-15	6766800	7205.26	0.1065	16123.69	0.00	54.68
C-15	6962800	18922.11	0.2718	28911.91	0.00	98.32
D-15	5843600	7708.16	0.1319	23237.21	0.00	60.51
B-15	5190400	1551.30	0.0299	16818.25	0.00	28.82
A-8	3614400	3100.70	0.0858	28633.09	0.00	67.97

5.3.3 LaHave River Watershed

The LaHave River watershed residual was excluded from the study due to its high exposure to ARD (32.16% of its area). I identified 15 catchments within subbasins A and B. The prioritization and site scoring results for the catchments are given in table 11 and figure 11). The top priority catchment within the LaHave River watershed is H-15 which has the highest road density and is located closest to the outlet of the main river. Strong considerations for ARD risk and permission from private owners need to be taken during the early planning stages for the liming of catchment H-15. Catchment H-15 has a high ARD risk with 91% of its area underlain by the Halifax formation; consideration for potential disturbance causing the exposure of the bedrock within the catchment is required. Additionally a large proportion of catchment H-15 is privately owned (93.1%) therefore communication with the private landowners is required during the early stages of planning. Although the high proportion of private land owners and ARD risk does require more preliminary work and consideration, catchment H-15 is highly accessible and has high connectivity, making it the top priority site for liming within the LaHave River Watershed.



Catchment scoring table

Name	Connectivity score	Accessibility score	ARD score	Ownership score	Total score
H-15	0	0	55	35	90
E-8	10	10	60	25	105
D-8	30	30	65	15	140
B-30	40	60	40	20	160
D-15	120	40	0	0	160
C-8	90	50	0	27.5	167.5
B-8	140	20	0	10	170
A-30	110	80	0	2.5	192.5
A-15	50	70	70	30	220
A-8	100	110	0	12.5	222.5
C-15	60	130	35	5	230
G-15	20	140	50	22.5	232.5
E-15	130	100	0	7.5	237.5
F-15	80	120	45	17.5	262.5
B-15	70	90	75	32.5	267.5

Figure 11 Scored catchments within the LaHave River watershed, Nova Scotia with the associated scoring table showing connectivity, accessibility, ARD (risk) and ownership (private) scores. The lower scores are of higher priority.

Table 11 Prioritization criterion values for catchments within the LaHave River watershed, Nova Scotia. Sites are listed from highest to least priority.

Name	Area (m^2)	Road Length (m)	Accessibility value	Connectivity length (m)	ARD risk (%)	Privately owned (%)
H-15	7443200	54555.70	0.7330	23412.77	91.00	93.10
E-8	4519200	23317.26	0.5160	23795.62	100.00	83.03
D-8	4314400	20111.54	0.4661	25511.84	100.00	64.70
B-30	28677200	81353.50	0.2837	26412.67	67.54	78.47
D-15	7590800	27779.25	0.3660	45750.40	0.00	17.93
C-8	4976400	17747.39	0.3566	36046.69	0.00	83.86
B-8	5670400	26730.94	0.4714	54093.88	0.00	52.64
A-30	17693600	42653.66	0.2411	43962.46	0.00	33.42
A-15	11234400	31266.15	0.2783	30741.69	100.00	87.19
A-8	8368400	15701.85	0.1876	36552.96	0.00	57.71
C-15	14034400	19990.57	0.1424	33477.91	33.61	39.89
G-15	13700800	18912.04	0.1380	24796.45	83.03	80.22
E-15	13454000	25853.94	0.1922	51617.65	0.00	40.87
F-15	10425200	15906.77	0.1526	34625.85	79.38	74.24
B-15	13975600	29751.38	0.2129	33927.62	100.00	89.99

5.3.4 Moser River Watershed

There were no watershed units within the Moser River watershed excluded during the exclusionary analysis; despite this a large amount of the catchment area was excluded due to the abundance of large lakes. Four catchments are identified within the Moser River watershed with two sites, B-15 and A-30, having the same score as lowest priority (figure 12, table 12). Catchment A-15 is the highest priority catchment; it is has high connectivity to the mouth of the main river, is the second most accessible site and has the second lowest risk for ARD exposure. Catchment A-15 has the highest proportion privately owned with 13.78%; this needs to be addressed early in the planning stage.

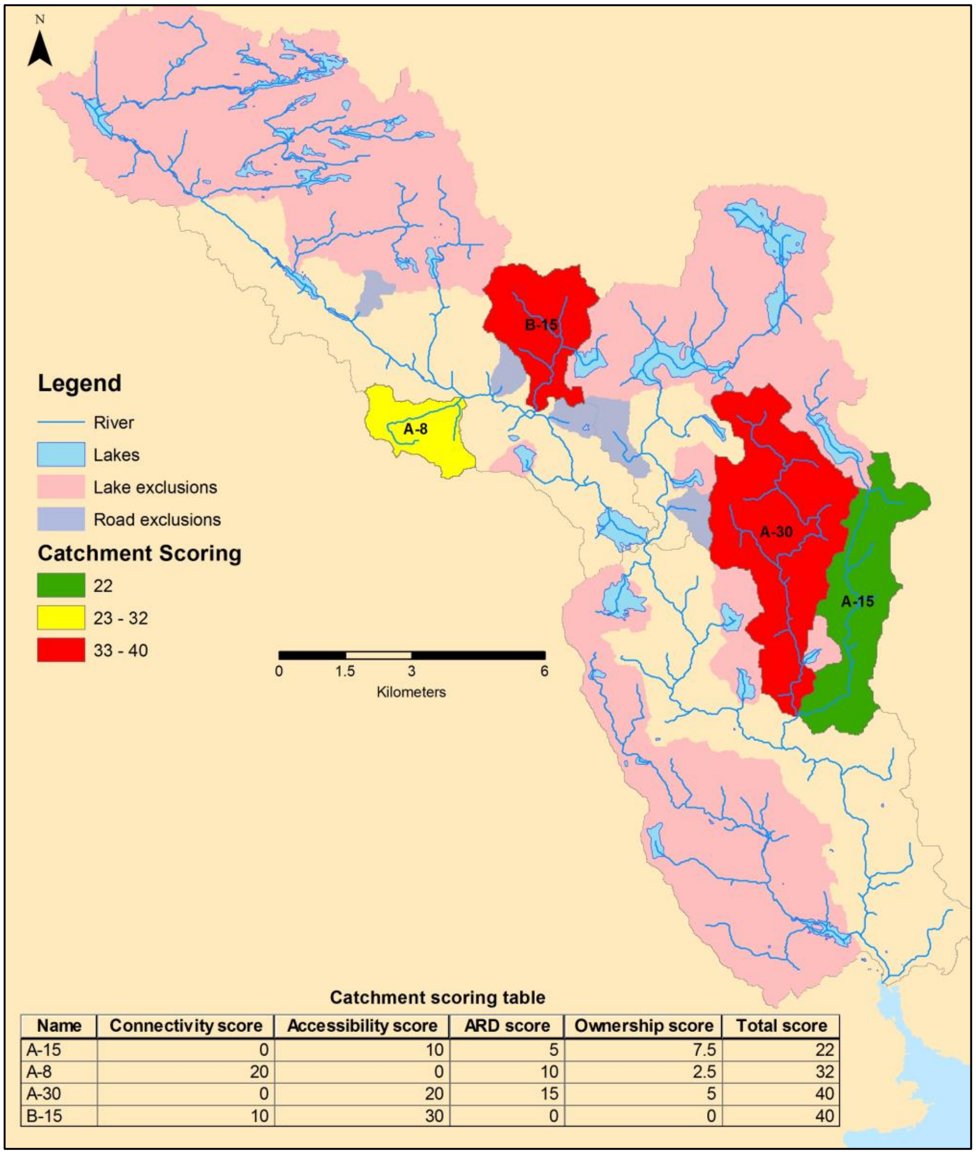


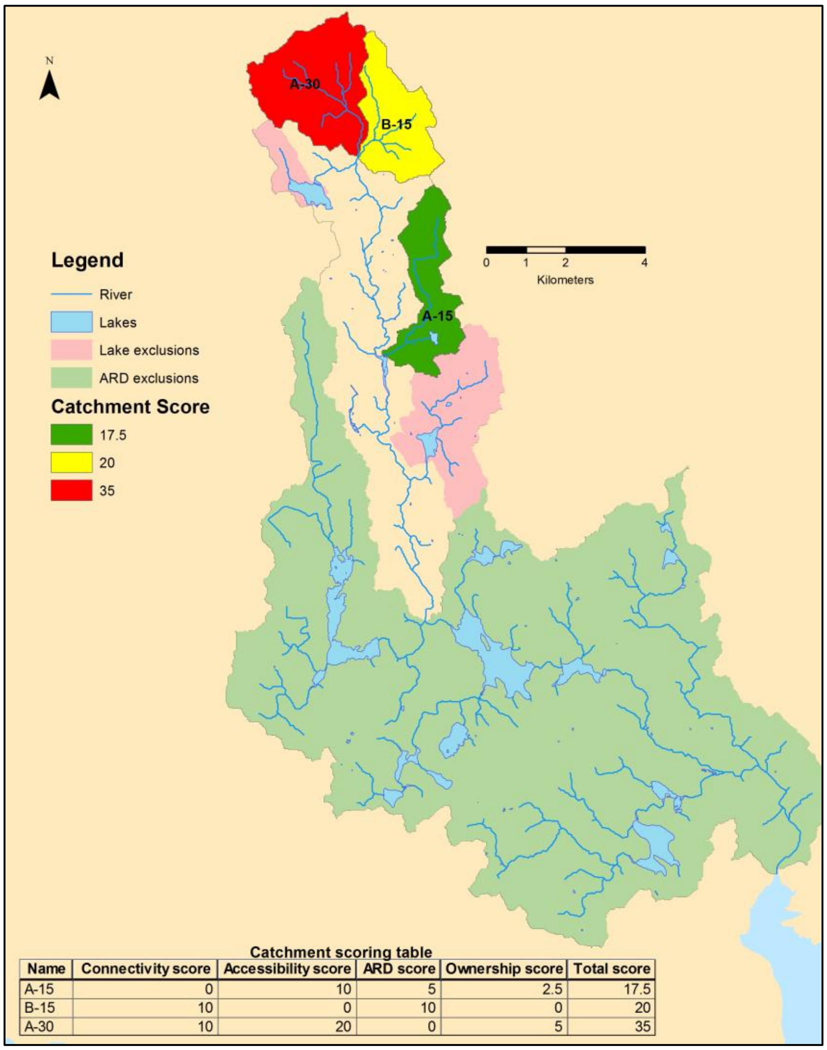
Figure 12 Scored catchments within the Moser River watershed, Nova Scotia with the associated scoring table showing connectivity, accessibility, ARD (risk) and ownership (private) scores. The lower scores are of higher priority.

Table 12 Prioritization criterion values for catchments within the Moser River watershed, Nova Scotia. Sites are listed from highest to least priority.

Name	Area (m^2)	Road Length (m)	Accessibility value	Connectivity length (m)	ARD risk (%)	Privately owned (%)
A-15	7789200	14428.82	0.1852	8789.21	33.94	13.78
A-8	3001600	7915.64	0.2637	22681.11	43.91	0.64
A-30	13760800	17359.7	0.1262	8789.21	47.88	12.16
B-15	5347200	4901.21	0.0917	20694.59	14.28	0.36

5.3.5 Sackville River Watershed

The Sackville River Watershed residual and subbasin A were excluded from the study due to the high level of ARD exposure with 25.38% and 15.21% area exposed, respectively. Three catchments were identified within the remaining watershed unit, subbasin B (figure 13, table 13). Catchment A-15 is of highest priority; it is located closest to the mouth of the main river, and is the second most accessible and at risk for ARD exposure of the three catchments. Additionally 32.29% of catchment A-15 is privately owned; this should be addressed in the early planning stages of terrestrial liming.



Name	Connectivity score	Accessibility score	ARD score	Ownership score	Total score
A-15	0	10	5	2.5	17.5
B-15	10	0	10	0	20
A-30	10	20	0	5	35

Figure 13 Scored catchments within the Sackville River watershed, Nova Scotia with the associated scoring table showing connectivity, accessibility, ARD (risk) and ownership (private) scores. The lower scores are of higher priority.

Table 13 Prioritization criterion values for catchments within the Sackville River watershed, Nova Scotia. Sites are listed from highest to least priority.

Name	Area (m^2)	Road Length (m)	Accessibility value	Connectivity length (m)	ARD risk (%)	Privately owned (%)
A-15	4780400	24662.14	0.2526	24662.14	17.45	32.29
B-15	4712800	30969.68	0.2728	30969.68	35.91	16.04
A-30	7193200	13682.29	0.1902	30969.68	0	57.60

5.2.6 Salmon River Watershed

Subbasin A and B of the Salmon River watershed was excluded from the study due to high ANC (5.64 mg L^{-1} and 5.34 mg L^{-1}, respectively). I have identified five catchments within the Salmon River watershed residual, with C-8 being of highest priority (figure 14, table 14). Catchment C-8 is top priority catchment for terrestrial liming within the Salmon River Watershed as it has the highest connectivity (located closest the mouth of the main river) and has the highest road density. Catchment C-8 does have a significant proportion of its area privately owned (39.09%), this should be addressed in the early planning stage. All catchments within the Salmon River Watershed have no risk of future exposure to ARD because they are not underlain by the Halifax Formation.

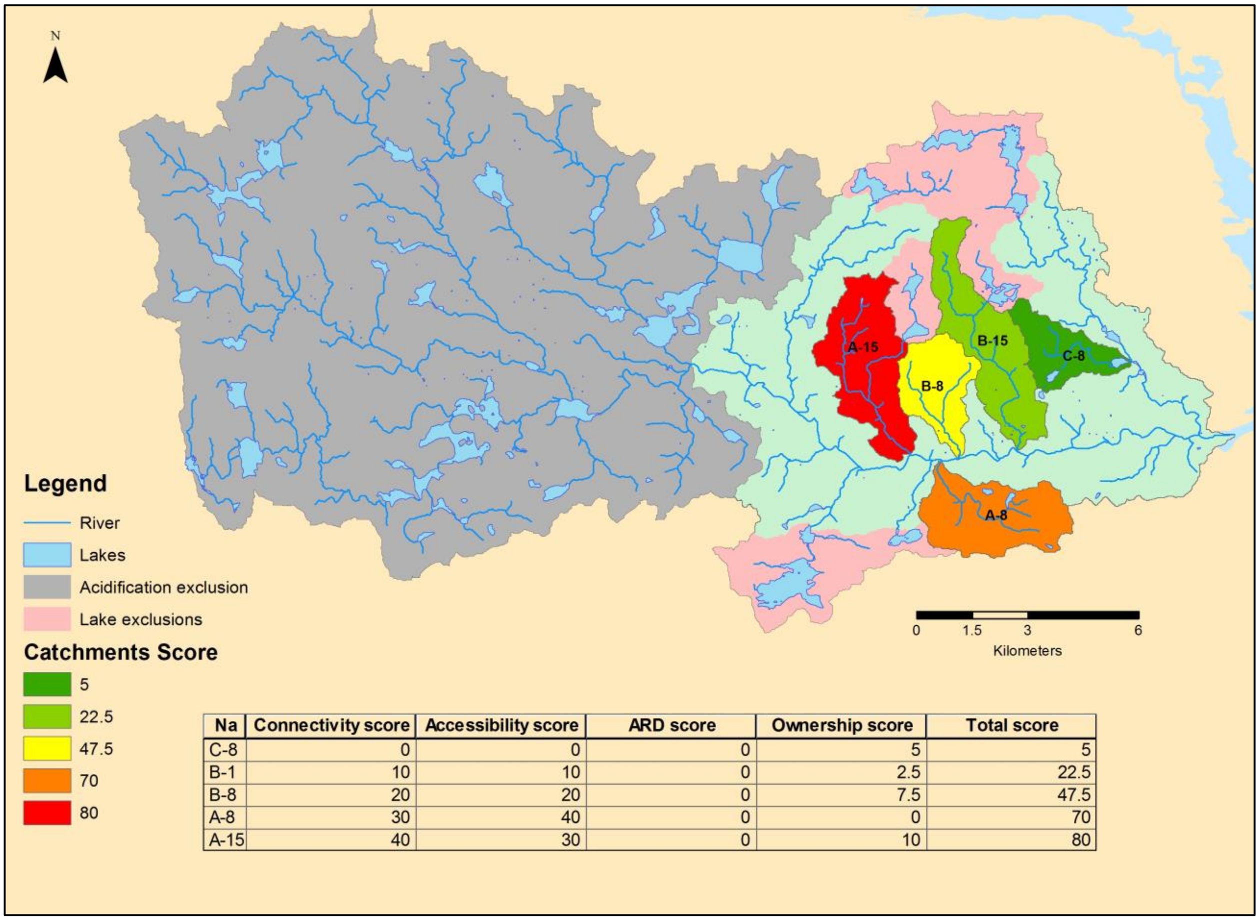


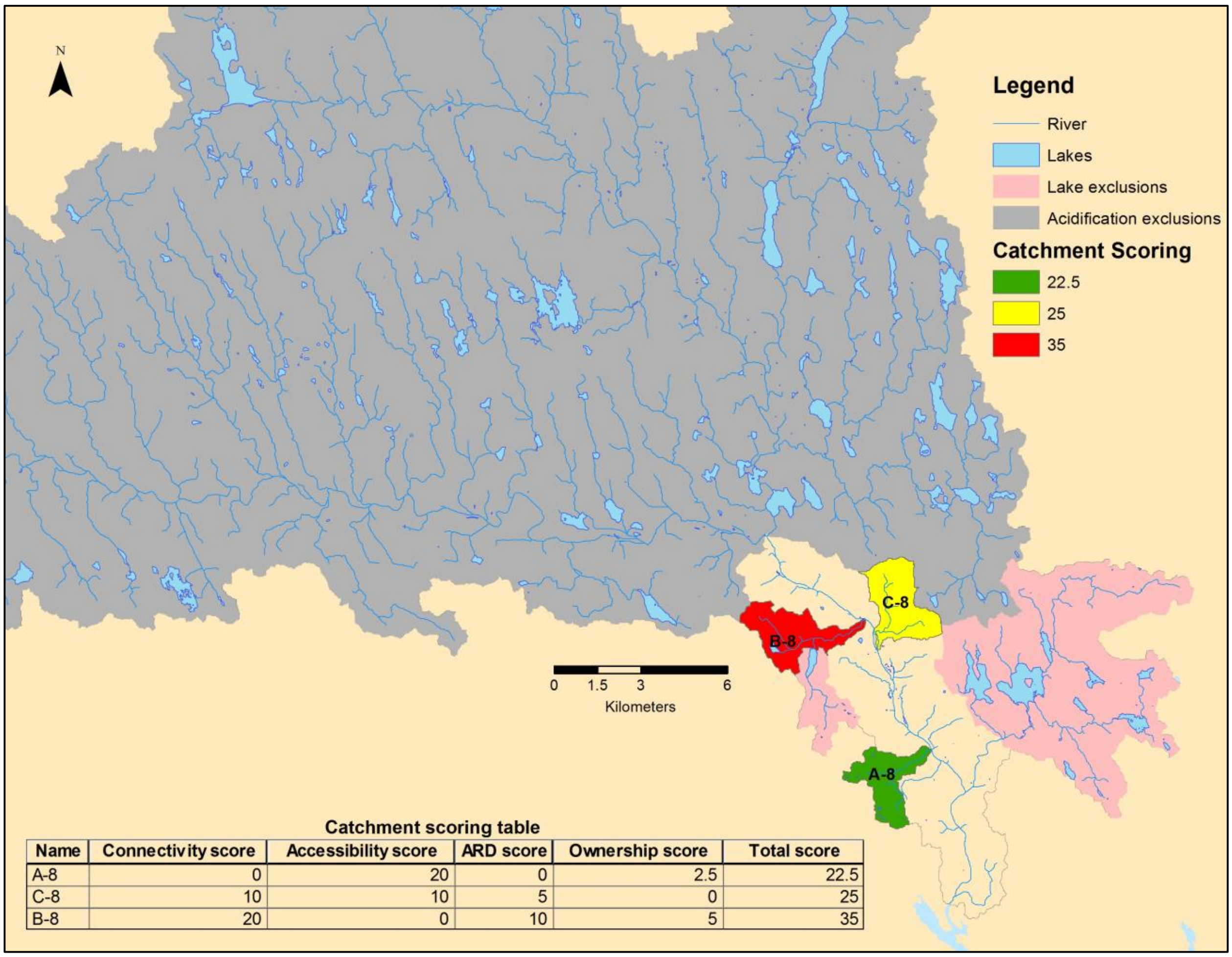
Figure 14 Scored catchments within the Salmon River watershed, Nova Scotia with the associated scoring table showing connectivity, accessibility, ARD (risk) and ownership (private) scores. The lower scores are of higher priority.

Table 14 Prioritization criterion values for catchments within the Salmon River watershed, Nova Scotia. Sites are listed from highest to least priority.

Name	Area (m^2)	Road Length (m)	Accessibility value	Connectivity length (m)	ARD risk (%)	Privately owned (%)
C-8	3702400	3776.47	14021.77	0.3787	0	39.09
B-15	8028800	5967.01	23013.68	0.2866	0	32.34
B-8	4548400	7999.8	12201.68	0.2683	0	45.87
A-8	6976800	8521.22	8473.22	0.1214	0	32.26
A-15	7905600	9460.63	11050.14	0.1398	0	48.87

5.2.7 St. Mary's River Watershed

A good proportion of the St. Mary's River watershed was excluded from the study. Subbasin A and B were excluded because of their high ANC values (5.04 mg L^{-1} and 9.41 mg L^{-1}, respectively). I identified three catchments within the residual, with A-8 being of highest priority (figure 15, table 15). Although catchment A-8 has the least road density and second highest proportion of area owned by private land owners (31.95%) of the three catchments, it has no risk of ARD exposure and is located closes to the mouth of the main river.



Name	Connectivity score	Accessibility score	ARD score	Ownership score	Total score
A-8	0	20	0	2.5	22.5
C-8	10	10	5	0	25
B-8	20	0	10	5	35

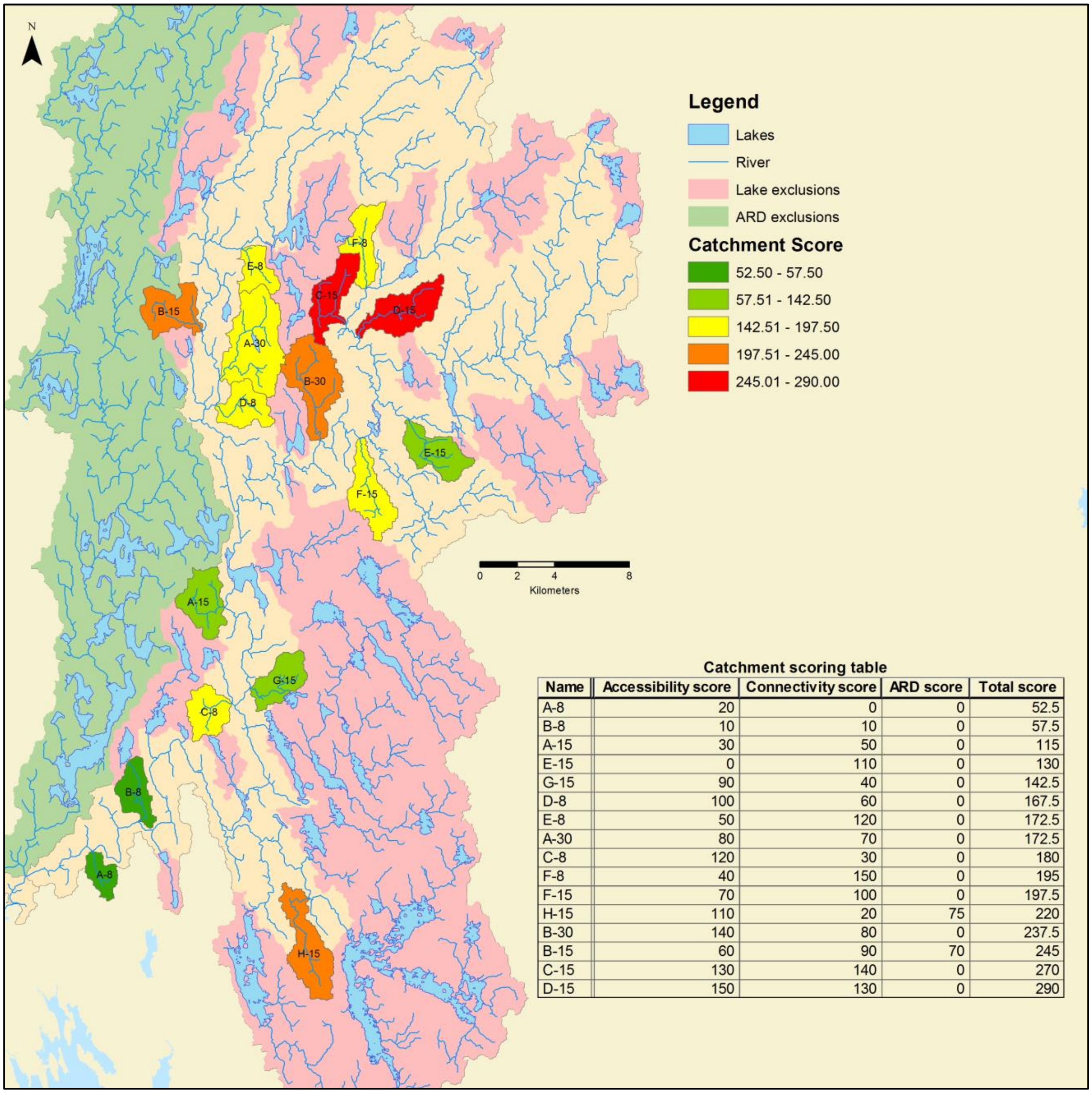
Figure 15 Scored catchments within the St. Mary's River watershed, Nova Scotia with the associated scoring table showing connectivity, accessibility, ARD (risk) and ownership (private) scores. The lower scores are of higher priority.

Table 15 Prioritization criterion values for catchments within the St. Mary's River watershed, Nova Scotia. Sites are listed from highest to least priority.

Name	Area (m^2)	Road length (m)	Accessibility value	Connectivity length (m)	ARD risk (%)	Privately owned (%)
A-8	3808000	3912.84	0.1028	6815.95	0	31.95
C-8	4816800	7153.41	0.1485	11248.4	24.21	3.19
B-8	4783200	9587.18	0.2004	12550.65	47.26	37.68

5.3.8 Tusket River Watershed

Although an entire subbasin (A) was excluded from the study due to its high ARD exposure (10.52%), the Tusket River watershed has the greatest number of catchments identified with 16 catchments within subbasin B and the residual (figure 16, table 16). Catchment A-8 is the top priority catchment; Catchment A-8 is the closest catchment to the mouth of the main river, has no risk of ARD exposure and is has the third highest road density of the 16 catchments. Unfortunately catchment A-8 has the second highest proportion of land privately owned (85.92%), which will need to be addressed early in the planning stages.



Catchment scoring table

Name	Accessibility score	Connectivity score	ARD score	Total score
A-8	20	0	0	52.5
B-8	10	10	0	57.5
A-15	30	50	0	115
E-15	0	110	0	130
G-15	90	40	0	142.5
D-8	100	60	0	167.5
E-8	50	120	0	172.5
A-30	80	70	0	172.5
C-8	120	30	0	180
F-8	40	150	0	195
F-15	70	100	0	197.5
H-15	110	20	75	220
B-30	140	80	0	237.5
B-15	60	90	70	245
C-15	130	140	0	270
D-15	150	130	0	290

Figure 16 Scored catchments within the Tusket River watershed, Nova Scotia with the associated scoring table showing connectivity, accessibility, ARD (risk) and ownership (private) scores. The lower scores are of higher priority.

Table 16 Prioritization criterion values for catchments within the Tusket River watershed, Nova Scotia. Sites are listed from highest to least priority.

Name	Area (m^2)	Road length (m)	Accessibility value	Connectivity length (m)	ARD risk (%)	Privately owned (%)
A-8	2847600	7008.96	0.2461	6681.81	0	85.92
B-8	4604400	11541.28	0.2507	12177.69	0	93.5
A-15	6532000	13480.03	0.2064	45051.92	0	92.21
E-15	6281600	18069.76	0.2877	72725.78	0	2.05
G-15	5494000	5095.72	0.0928	38286.1	0	0.39
D-8	5183600	4260.27	0.0822	59782.16	0	0.33
E-8	3727200	6877.58	0.1845	73616.66	0	0
A-30	13591600	13648.81	0.1004	61359.56	0	3.72
C-8	4990800	3952.83	0.0792	36901	0	45.85
F-8	5488000	11005.68	0.2005	78917.05	0	0.23
F-15	7126400	8721.82	0.1224	66468.23	0	27.34
H-15	9107200	7399.99	0.0813	36356.74	47.45	0.4
B-30	10344000	5207.13	0.0503	61766.08	0	1.03
B-15	6527200	8423	0.129	64936.62	13.19	5.01
C-15	6527600	4504.55	0.069	76237.98	0	0
D-15	7897600	3164.01	0.0401	74797.74	0	0.35

5.3.9 West River Watershed

There is only one suitable catchment for terrestrial liming within the West River watershed (figure 17, table 17). I found a lack of suitable catchments within the West River watershed because of the limited potential liming areas due to the exclusion of its subbasin B due to high exposure levels of ARD (6.05% of its area) and because of the lake exclusions in subbasin A. I have included a table of the prioritization analysis results for the West River because this information may be useful to decision-making in the future.

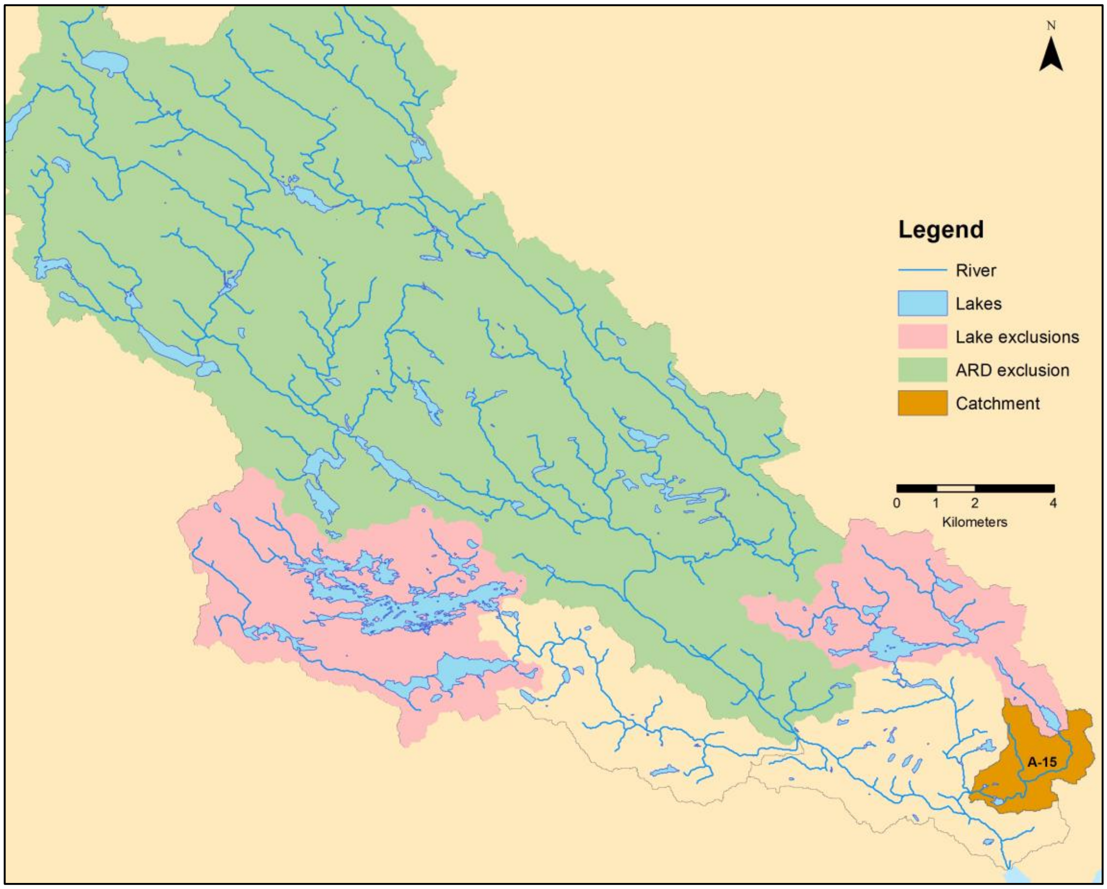


Figure 17 Catchment identified within the West River watershed, Nova Scotia.

Table 17 Prioritization criterion values for the catchment identified within the West River watershed, Nova Scotia.

Name	Area (m^2)	Road Length (m)	Accessibility value	Connectivity length (m)	ARD risk (%)	Private ownership (%)
A-15	5166000	6391.32	0.1237	2885.34	0	1.477594

5.4 Invasive Species Distribution Results

The distribution of the invasive fish species Smallmouth Bass and Chain Pickerel is an important consideration when determining what watershed to focus conservation efforts on. I have created a GIS layer of Smallmouth Bass and Chain pickerel distributions in Nova Scotia based on invasive species distribution data provided by DFO (figure 18). The invasive species distribution data includes 242 records of Smallmouth Bass distribution and 97 records for Chain

Pickerel with each record indicating the location where that particular species was observed. In addition I have provided a table describing invasive fish presence within the seven watersheds that suitable for liming (see table 18).

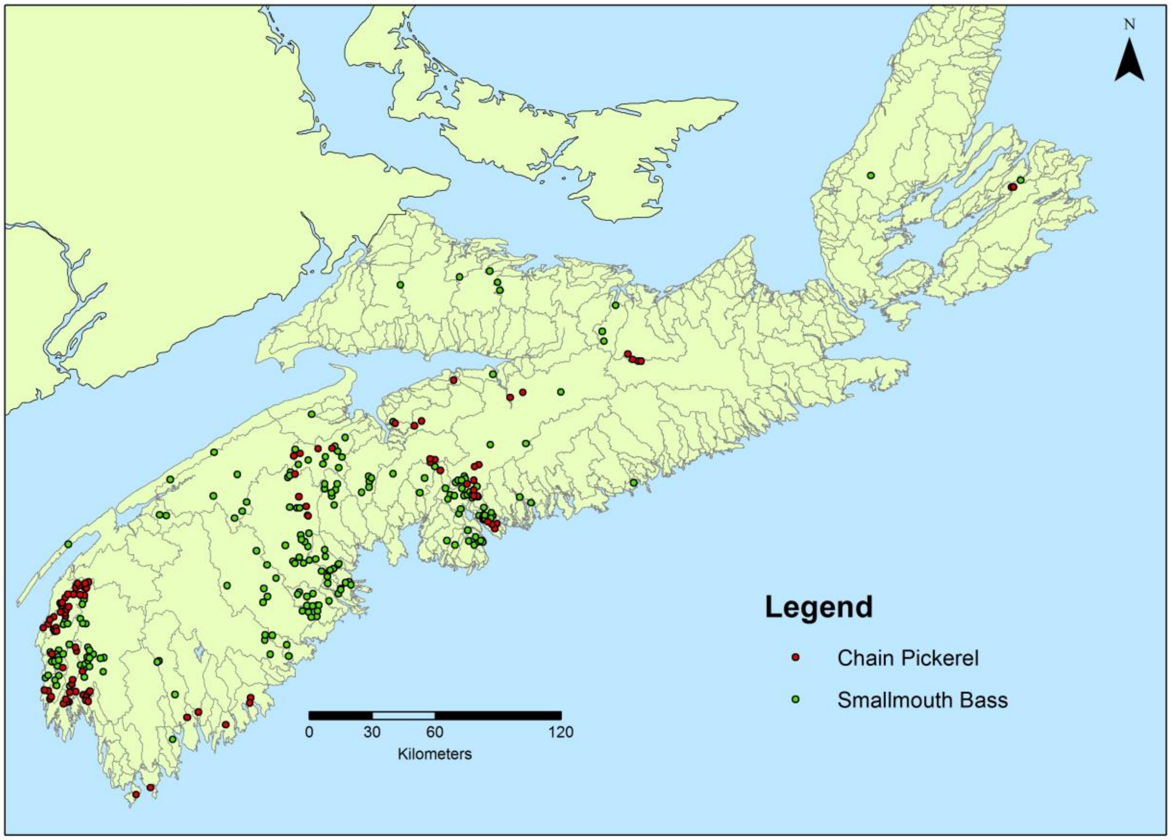


Figure 18. Distribution of Chain Pickerel and Smallmouth Bass in Nova Scotia. GIS layer is based on DFO's invasive fish database. Watershed layer from Sterling et al. (2014-b).

Table 18. Number of recorded Chain Pickerel and Smallmouth Bass based on DFO's invasive fish database.

Watershed name	Chain Pickerel Number	Smallmouth Bass Number
Country Harbour	0	0
Gold River	0	7
LaHave River	4	18
Moser River	0	0
Sackville River	0	0
Salmon River	0	0
St. Mary's River	0	0
Tusket River	2	20
West River	0	0

5.5 Key Information Needs Identified

I have identified key information needs for watershed management and terrestrial liming in Nova Scotia. Nova Scotia freshwater systems face a variety of environmental and anthropogenic stressors (i.e., acidification, ARD, mining) that are not well understood because of the sparse ground-based aquatic monitoring in the province (Sterling et al., 2014-b). Reduced government funding for freshwater monitoring has limited the capacity of watershed level management initiatives to effectively restore and mitigate against environmental stressors such as acidification in SWNS. Although the Nova Scotia Watershed Assessment Program (NSWAP; Sterling et al., 2014-b) provided a high-level assessment to map environmental stressors and threats to indicate which watersheds to focus management efforts, the project identified the need for a local-scale detailed watershed assessment. Due to the lack of well-representative high resolution data for the priority watersheds I used indices for the assessment of important watershed attributes such as the ANC_G interpolated layer as a proxy for acidification for the exclusionary analysis. The selection of exclusionary and prioritization criteria was limited by data availability and therefore I am able to further identify the local-scale detailed watershed assessments that would be necessary to include in the development of a more effective model for prioritizing catchments for terrestrial liming (table 19).

Table 19 key watershed assessments needed for improved terrestrial liming catchment selection in Nova Scotia.

Assessment	Importance for catchment selection model
pH survey	Accurately characterize acidification status of watersheds in NS and identify watersheds with highest risk of SU extirpation
Aluminum Survey	Identify which watersheds may have ionic aluminum concentrations about the toxicity threshold and recommend specific application strategies that will target the source area
Fish passage survey	Identify impassable fish barriers and salmon habitat that cannot be reached by salmon
Critical salmon habitat	Identify and map critical salmon habitat in Nova Scotia. Terrestrial liming efforts should be focused on improving critical salmon habitat.
Invasive species data	Update invasive species data and identify the current range of invasive fish in Nova Scotia. Priority liming catchments should not fall within this range.

6.0 Discussion

6.1 Significance of Research for Terrestrial Liming in SWNS

This research represents the first comprehensive and qualitative identification and assessment of catchments for terrestrial liming described in the literature. This research improves upon the pioneer study by MTRI that identified catchments within the Gold, LaHave and Medway watersheds but lacked a quantitative assessment of the potential liming sites within the key watersheds within the target species (SU salmon) range. Although catchment site selection for terrestrial liming is not crucial for effective liming in other regions, such as Sweden and Norway, the unique topography, soils and bedrock of Nova Scotia requires identification and prioritization of catchments that will support effective liming (personal communication with Dr. Atle Hindar). The objective to most freshwater liming projects are to improve water quality for a target species; I have developed a model to identify and prioritize catchments that will best support effective terrestrial liming and the SU salmon population.

The catchment prioritization model detailed in this paper helps meet the need of government and community groups for the identification and prioritization of catchments for terrestrial liming to focus and improve SU salmon conservation efforts. I have identified catchments within the 13 SU priority watersheds as the primary units of SU salmon conservation when using terrestrial liming efforts to improve habitat quality. I will be developing a Terrestrial Liming Guidebook for SWNS that will provide detailed information on the priority liming catchments within the nine critical liming watersheds. The Terrestrial Liming Guidebook will be made available to the government, community groups and the public to provide information to decision-makers that can help them make informed decisions on where to focus terrestrial liming efforts to best support the SU salmon population.

6.2 Other Considerations for Terrestrial Liming in SWNS

There are several important aspects of terrestrial liming and site selection that were outside the scope of this research or that I was unable to address due to limited data availability. Although terrestrial liming has been studied since the 1970's in Sweden and Norway it has not been well characterized in Nova Scotia, thus there are key considerations unique to terrestrial liming in SWNS. Additionally, due to limited data availability (table 19) and duration of this research (undergraduate honours thesis), several important attributes or criterion were not included in the model. Important considerations for terrestrial liming in SWNS not represented in the model include the dose-response rate for terrestrial liming and considerations for aluminum concentrations, invasive fish distributions and fish barriers; these are described in detail below.

Dose-response rate in SWNS

The dose-response rate for terrestrial liming and water improvements (increase pH, decreased metals) varies based on location and is influenced by the local geology, topography, calcium budgets and the type of buffering material applied (Sterling et al., 2014-a). Unfortunately the dose-response rate for terrestrial liming in SWNS is not well-characterized. There is only one experimental terrestrial liming site in SWNS located in the small Maria Brook catchment within the Gold River watershed but future statistical analysis is needed to determine a dose-response relationship for the region (Sterling et al., 2014-a). The uncertainty in the dose-response rate in SWNS remains an issue for future terrestrial liming projects.

Ionic aluminum concentrations

Ionic aluminum is mobilized during low pH conditions (Bache, 1986) and attaches to the negative epithelium of the fish gills causing respiratory issues and, in many cases, mortality (Baker and Schofield, 1982; Lacroix and Townsend, 1987; Peterson et al., 1989). Although it was historically believed not to be an issue in SWNS (Lacroix and Townsend, 1987; Peterson et al., 1989), recent studies suggest that ionic aluminum concentrations often exceed the EIFAC toxicity threshold of 15 ug L^{-1} and therefore may be a limiting factor to the SU salmon population (Dennis and Clair, 2012; MacLeod et al., 2015). Lime must be applied to all areas of the catchments with high ionic aluminum to ensure that the critical source areas for aluminum are targeted. If the critical source areas for aluminum are not limed then ionic aluminum may remain a limiting factor to the SU salmon despite the liming efforts.

Invasive species distributions

The Invasive fish Chain Pickerel and Smallmouth Bass compete with the SU salmon and have been found in several of the thirteen priority watersheds (table 18). The current DFO database of the occurrence of these species in freshwater systems in Nova Scotia is small, outdated and does not likely well represent the true range of the invasive fish (section 5.4). Liming a catchment containing invasive fish species will not as well support an increase in the SU salmon population compared to liming a catchment free of invasive species.

Fish Barriers

Fish barriers are identified as a significant limiting factor to the SU salmon population in SWNS (DFO, 2013). An impassable barrier, such as a poorly maintained culvert, removes all habitat upstream and can significantly reduce habitat availability for the SU salmon. It is hard to map the location of physical barriers and include them in the model because the structures can be seasonally impassable during different flows and different salmon life stages. Understanding the stream accessibility within and downstream of a potential liming catchment is important as liming a catchment located upstream of an impassable barrier will have no impact on the SU salmon population.

The dose-response relationship in SWNS, the ionic aluminum concentration of a potential liming catchment and the invasive fish distributions and location of fish barriers in proximity to a liming catchment should be considered during the planning stages of terrestrial liming. It is important to note that these considerations were not incorporated into the model developed for this research but that they will be articulated in the Terrestrial Liming Guidebook to inform decision-makers of their potential impacts on the liming project.

6.3 Future Work

6.3.1 Recommendations to Improve the Model

I have developed a model that identifies catchments that best support effective liming and the SU salmon within the 13 SU priority watersheds. The catchment prioritization model includes four exclusionary criteria (acidification, current ARD, accessibility and must not drain into a large lake) and four prioritization criteria (connectivity, accessibility, ARD risk and ownership) that support effective and feasible liming and the SU population. Although I have met the objectives of this research project by identifying priority liming sites, there are several key recommendations that will improve the model's accuracy which should be considered in future terrestrial liming site selection.

The incorporation of local knowledge in site selection processes is critical to the success of projects where there is limited monitoring and data availability. One of my main research tools was consultation with the Southern Upland Collaborative Projects Working group which involved a variety of stakeholders including government, community, and academic representation. I used local knowledge gained from stakeholder consultation in the selection of the exclusionary and prioritization criteria; this supported the identification of catchments that are feasible to lime through consultations with the groups who would lead future liming initiatives, and that also best support the SU population through sharing of information with fish biologists and experts with DFO. I have identified potential for the incorporation of local scale water quality data into the model through consultation with local community groups but unfortunately, due to limited time, was unable to aggregate and include this data within the current model. For example there is local scale water quality data available for the Gold River, LaHave River, St. Mary's River and West River watersheds which could be incorporated into the model to better represent the acidification status of these watersheds. I recommend that local knowledge and the data available from local community groups are incorporated into future models to more accurately identify catchments most suitable for terrestrial liming.

There are additional catchment attributes that impact the effectiveness of terrestrial or that would best support the SU population that were not included in the model due to limited time and data availability. Section 6.2 described two factors that should be considered in future models: invasive species distributions and fish barriers. Unfortunately due to limited data availability invasive species distributions and fish barriers were not incorporated in the model. Future models should give higher priority to catchments not containing invasive species and include permanent fish barriers as an exclusionary criteria, excluding catchments that are located upstream of an impassable barrier. In order to ensure that crucial exclusionary and prioritization criteria are included in future models I suggest the incorporation of stakeholder consultation in the planning and development stages of the model.

A major limitation to the catchment prioritization model described in this research is the poor resolution of the analysis. The objective of this study is to identify the most suitable catchments for terrestrial liming within the 13 SU priority watersheds. The large study area and short duration of this research (undergraduate honours thesis) required a poor resolution exclusionary analysis where the N-1 subbasins and residuals of the priority watersheds were the watershed units of analysis that were excluded from the study (section 3.3.1 and 5.1); this allowed for a simple reduction of the study area to a more manageable size. For example N-1 subbasins and residuals were excluded if the average ANC_G was greater than 5 mg L^{-1}; although this allowed for an easy exclusion of nine watershed units, it potentially excluded smaller catchments that have an ANC_G less than 5 mg L^{-1} that may be suitable for terrestrial liming. To avoid excluding potentially suitable liming catchments I recommend that future models either perform a series of local watershed scale assessments when looking to identify and prioritize catchments within multiple watersheds (i.e., as in this study) or that the liming project is delimited to one watershed of interest to allow for more accurate measurements for key criteria.

My final recommendation for future catchment prioritization models is a sensitivity analysis that will allow the decision-maker to assess how the output is changed with the exclusion of different criterion and/or with varying threshold values for the criterion. For example a sensitivity analysis for the acidification criterion can identify what catchments may be identified or excluded at varying ANC_G threshold values. Unfortunately I was unable to perform a sensitivity analysis due to time limitations but is important for future models to allow for more informed decisions on where to focus terrestrial liming efforts.

6.3.2 Recommendations for Future Terrestrial Liming Projects

The planning stage of a terrestrial liming project is crucial to its success in achieving project objectives. The planning of a terrestrial liming project should include the collaboration of multitude of stakeholders (i.e., government, scientists and community groups). The probability of encountering project issues during lime application or water quality monitoring can be reduced by incorporating stakeholders that provide an element of local knowledge. After the creation of a planning committee a terrestrial liming project is recommended to follow a five step decision process that involves decisions involving (figure 19).

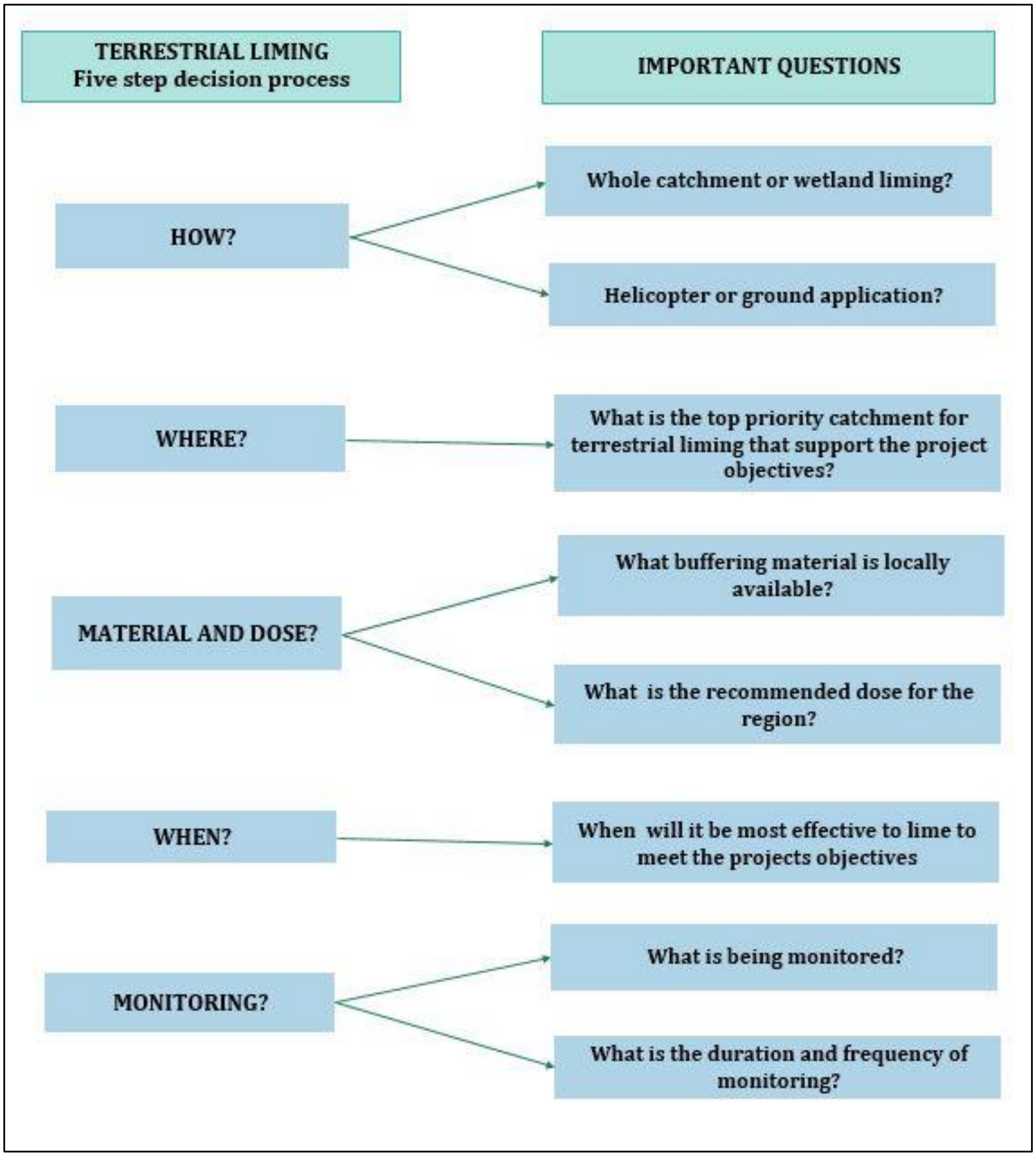


Figure 19 Flowchart of the steps for terrestrial liming project planning and associated key questions to be considered.

The planning committee should carefully consider each of the five steps prior to terrestrial liming application and answer the important associated questions to increase the probability of effective terrestrial liming. The catchment prioritization model I have developed with this research will help answer step two in the planning decision process by identifying catchments that best support effective liming and the target population. An interdisciplinary planning committee can help answer the important questions associated with each of the steps in the decision process which may require additional research and incorporation of local knowledge.

7.0 Conclusion

The objective of my research is to decrease the risk of SU salmon extirpation in SWNS by increasing the effectiveness of terrestrial liming through the identification of the best locations to lime. To meet the research objective I developed the first comprehensive and quantitative model to prioritize catchment for terrestrial liming in SWNS. Using local knowledge gained through stakeholder consultation and GIS technology I selected four exclusionary and prioritization criteria that help to identify and prioritize the most suitable catchments to meet the research objectives. Using the catchment prioritization model I identified the top priority catchments that have the most promise for effective liming and supporting the SU salmon population. In addition, I identified the information needed to improve the model. This research has clearly demonstrated the need for improved water quality data, at both provincial and local scales, to improve future terrestrial liming catchment selection in Nova Scotia.

The catchment prioritization model and the results of this research will be published in a Terrestrial Liming Guidebook for SWNS in spring 2015. The priority catchments are the recommended units of conservation for the SU salmon when using terrestrial liming ground application methods for acidification mitigation in Nova Scotia. The catchment prioritization model is flexible and can be used by decision-makers to identify the priority catchments for terrestrial liming while considering multiple selection criteria. This research represents an important focus of SU conservation towards more informed decision-making and catchment selection to identify the most suitable sites to focus terrestrial liming mitigation efforts.

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10.0 Appendix

10.1 Watershed Delineation Methods

Required research tools:

- ArcGIS with Spatial Analyst
- ArcHydro

Required data:

- DEM
- Provincial Water flow

Steps to the watershed delineation, all steps use the ArcHydro toolbox:

1. Create a hydrologically conditioned DEM using the following:

   a. DEM Reconditioning: (DEM manipulation>terrain processing)
      *if unsure about the watershed boundaries may want to buffer around your study area.
   b. Fill Sink: (DEM manipulation>terrain processing)

2. Run the following 8 tools all under terrain processing toolbox:

*unless specified keep all default settings

   a. Flow Direction
   b. Flow accumulation
   c. Stream definition
      -Change the number of cells to 1000, giving an area of .4 km^2
      -note: if you want to want to show more streams (lower flow accumulation) then decrease number of cells and if you want to show less (higher flow accumulation) then increase number of cells.
   d. Stream segmentation
   e. Catchment grid delineation
   f. Catchment polygon processing
   g. Drainage line processing
   h. Adjoint catchment processing

Catchment delineation:

Define pour points of each catchment by using the point delineation tool in the ArcHydro tool box. Zoom in on a section of the drainage line and place the blue dot in the cell that you would like to delineate the drainage basin of (all cells that flow into that cell).

10.2 GIS Methodology: Exclusionary Criteria 1

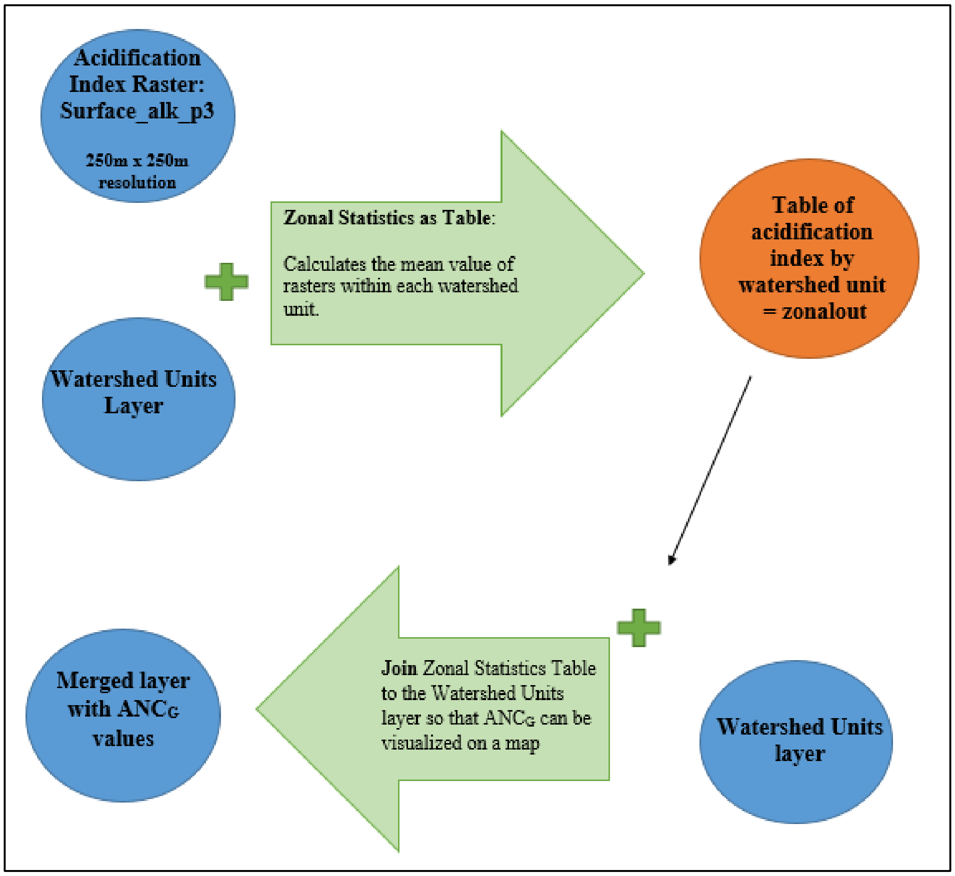

Figure A.1. Visual representation of the GIS methodology for calculating mean ANC_G for each watershed unit using ArcGIS 10.1. The mean ANC_G values will be used for exclusionary criteria, criterion 1 (catchments must be acidified).

10.3 GIS Methodology: Exclusionary Criteria 2

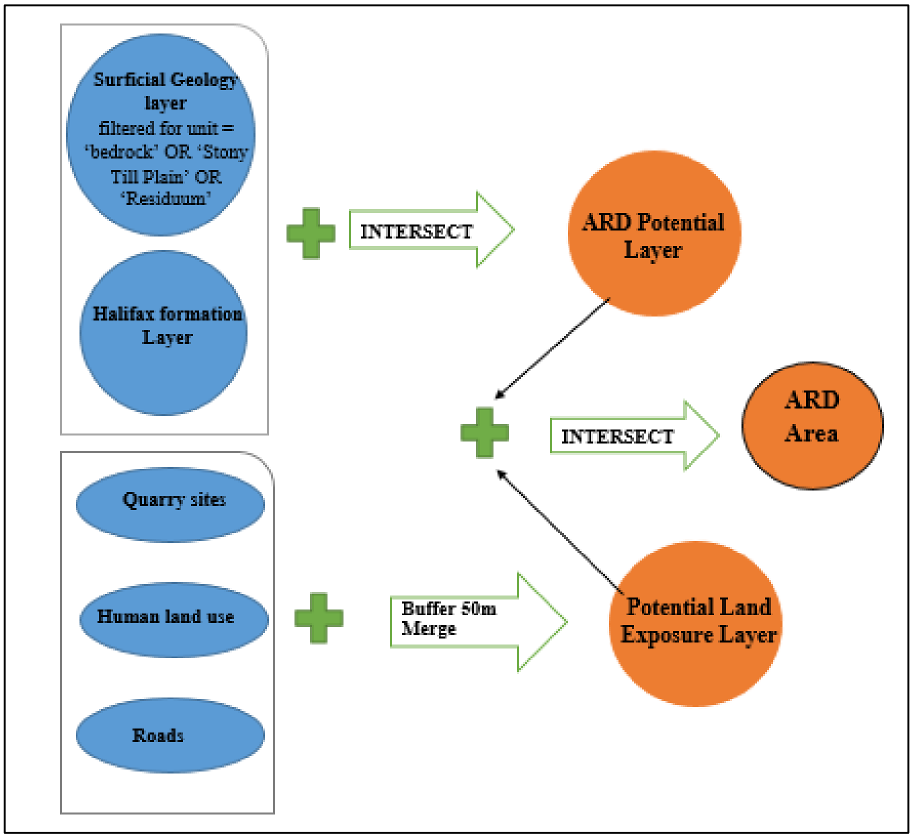

Figure A. 2. Visual representation of the GIS methodology used to calculate the Acid Rock Drainage (ARD) currently occurring in South Western Nova Scotia used for exclusionary criteria, criterion 2.

10.4 Stream Gradient GIS Methodology

<u>What is needed?</u>

1. Stream line
2. DEM

<u>Steps:</u>

1. Simplify line – this will remove unnecessary vertices in the river polyline.
    - (cartography tools>generalize>simplify line) * with 50 m max allowable offset

2. Densify line -- will add vertices along the river polyline at a user set length
    - (arc toolbox> editing tools> densify) * with max line distance of 84.9 m

3. Split line at vertices – this will split the river polyline at all vertices sites
    - (arc toolbox>data management>features>split line at vertices).

4. Add surface information – this will add the slope information from the DEM to the line.
    - (arc toolbox>3D Analyst>functional surface>add surface information).

    *make sure to "calculate geometry" for the new line segments to get proper river length calculations.

<u>Determining stream length at a specific stream gradient:</u>

In order to determine the length of rearing habitat within a catchment I made the assumption that all streams at a .12%-5% stream gradient were rearing habitat. This assumption was made because there was no other critical habitat data available for the study area.

To only have stream segments that fall within the stream gradient I used the following Structured Query Language (SQL) expression for the stream layer with the surface information:

SELECT* FROM (stream gradient) > .12% And (stream gradient) < 5%

10.5 Minimum Rearing Area Requirement: Calculation Method

Parameters that remain constant:
R_{sm}= ratio small salmon in population = 0.23
R_{lg} = ratio large salmon in population = 0.77
$1WS_{pf}$ = proportion small female salmon in population = 0.457
MWS_{pm}= proportion large female salmon in population = 0.917
F_{sm} = fecundity for small salmon = 3195 eggs/female
F_{lg} = fecundity for large salmon = 6,310 eggs/female
W = assumed stream width=2.6

Parameters that are user determined:
N = target population size
A_r = egg area requirement

Step 1: determining number of number of small to large salmon in population

1WS = # small salmon = N * $1WS_{pf}$ = N* 0.457
MWS = # large salmon = N* MWS_{pm} = N* 0.917

Step 2: calculate the number of eggs produced by the population

E_{sm} = # eggs produced by small salmon = 1WS * $1WS_{pf}$ * F_{sm} = 1WS * 0.457 * 3195
E_{lg} = # eggs produced by large salmon = MWS * MWS_{pm} * F_{lg} = MWS * 0.917 *6310
E_t = total # of eggs produced by population = E_{sm} + E_{lg}

Step 3: determine rearing area and length of stream with rearing area required for a catchment

A = rearing area required = E_t / A_r
L = length required = A/W = A/2.6