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Review of information to guide the identification of Critical Habitat in the riparian zone for listed freshwater fishes and mussels

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Foreword

This series documents the scientific basis for the evaluation of aquatic resources and ecosystems in Canada. As such, it addresses the issues of the day in the time frames required and the documents it contains are not intended as definitive statements on the subjects addressed but rather as progress reports on ongoing investigations.

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ABSTRACT

Fisheries and Oceans Canada's Species at Risk Program provides protection of the habitat necessary for the survival or recovery of listed freshwater fishes and mussels. It is well documented that the riparian zone is essential for the maintenance of freshwater aquatic habitats, fishes, and mussels. Despite this extensive body of literature, riparian features are not consistently included as Critical Habitat for listed freshwater fishes and mussels. An evidence based approach was required to guide the identification of features in the riparian zone as Critical Habitat. Riparian Critical Habitat are riparian features that: maintain the quality of aquatic features identified as Critical Habitat, and are directly used by fishes and mussels. We performed a literature review to determine the relevant riparian features, and the processes by which they affect aquatic features and water quality attributes. From these literature reviews we identified seven main processes by which riparian features affect aquatic features and water quality attributes: erosion, filtration, infiltration, isolation, meandering, shading, and subsidization. In addition, we identified riparian features that may directly support freshwater fishes and mussels' functions depending on their life history. Meta-analyses, reviews, and primary research articles were assessed to provide some guidance on the extent of riparian habitat required to support these seven processes. We outlined the current state of the literature regarding the extent of habitat required, and denoted where more empirical evidence is required. The dependencies of each process on attributes of the floodplain and other important considerations were summarised and can be consulted to determine what riparian features should be protected as Critical Habitat for a listed species. We have included additional resources to aid in the application of this guidance when defining the geographical area to be protected. Finally, five case-studies were used to provide an example of how practitioners may apply the guidance provided here to determine riparian Critical Habitat for a listed species.

INTRODUCTION

The Committee on the Status of Endangered Wildlife in Canada (COSEWIC), an independent advisory panel to the Minister of Environment and Climate Change Canada, assesses the conservation status of wildlife species based on a status report (Figure 1). Members of COSEWIC are wildlife biology experts from academia, government, non-governmental organizations, the private sector, and indigenous knowledge-holders.

Once COSEWIC has assessed a given species as special concern, threatened, endangered, extirpated or extinct, the Minister of Environment and Climate Change Canada (ECCC) considers the species for listing under *Species at Risk Act* (SARA). ECCC sub delegates the assessment of aquatic species to the Minister of Fisheries and Oceans Canada (DFO). Depending on their status, species at risk are listed in one of following categories: data deficient, special concern, threatened, endangered, extirpated or extinct (Figure 2). Under the *Act*, species or designatable units (DUs) listed as threatened, endangered or extirpated and their critical habitats receive protection. The most current List of Wildlife Species at Risk in Canada is available at the Species at Risk Registry website.

The goals of the *Species at Risk Act* are to avoid wildlife species from becoming extinct or extirpated, help with the recovery of threatened, endangered or extirpated, species, and ensure that species of special concern do not become threatened or endangered.

There are many anthropogenic and natural threats that may endanger wildlife species. The International Union for Conservation of Nature (IUNC) threat categories that can impact freshwater aquatic resources include (Salafsky et al. 2008; Faber-Langendoen et al. 2012; Master et al. 2012):

- **Residential and commercial development** – Housing, urban, commercial, industrial, tourism, and recreation areas can all alter or destroy habitat such that it is a detriment to a species.
- **Agriculture and aquaculture** – Agriculture and aquaculture can cause pollution, and aquaculture can lead to negative species interactions resulting from escapees, and disease and pathogen transmission.
- **Energy production and mining** – Mining and quarrying can result in habitat loss or degradation if it occurs below the high water mark or in the floodplain.
- **Transportation and service corridors** – Roads, railways, utility and service lines can modify or reduce habitat and may result in barriers to movement.
- **Biological resource use** – Fishing and harvesting aquatic resources; either by targeted fishing for a particular species or as incidental harvesting such as fisheries bycatch can affect a the fish community, logging and wood harvesting; forestry activities or gathering terrestrial plants; removal of terrestrial plants for control (i.e., invasive species).
- **Human intrusions and disturbance** – Recreational activities, works and activities can modify habitat, reduce fitness or kill individuals.
- **Natural system modifications** – Fire and/or fire suppression, dams, water management, and other ecosystem modification that can alter habitat.
- **Pollution** – Discharge of household/urban waste, industrial, military, agricultural and forestry effluents, garbage and solid waste, and air-borne pollutants into the environment may impact species abundance.

- **Geological events** – Volcanoes, earthquakes, tsunamis, avalanches, and landslides can destroy or severely alter habitat where they occur.
- **Climate change** – Climate change can result in habitat shifting and alteration, droughts, temperature extremes, storms, and flooding making it difficult or even impossible for many species to survive in their current distribution range.

In most instances, more than one of these anthropogenic or natural factors is having an impact on biodiversity. While some of the listed threats may act directly on the aquatic habitat, many occur outside of the aquatic habitat in the riparian zone, i.e., the area between the high water mark and the upland area. The following threats are likely to act in particular on the riparian habitat: residential and commercial development, agriculture, forestry, mining, road crossings, and recreational activities.

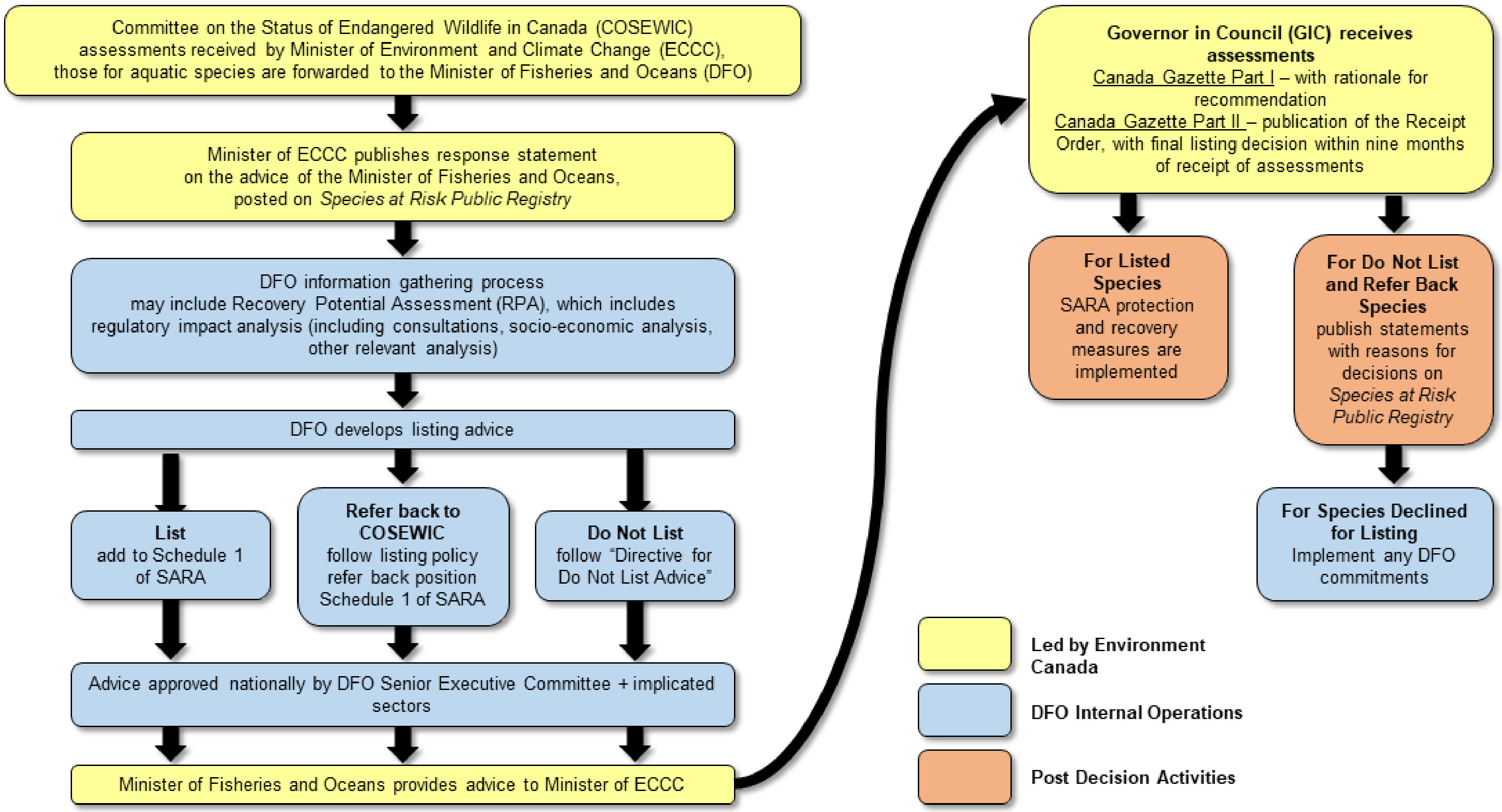

Figure 1: Listing process for Species at Risk.

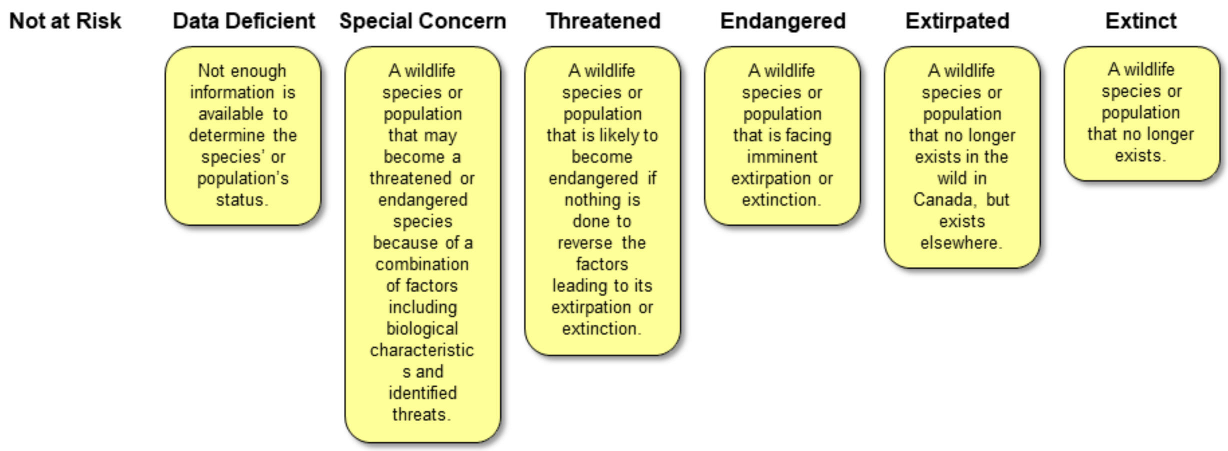

Figure 2: Species at Risk categories. Every Recovery Strategy and Action Plan developed for a species listed in Schedule 1 of the Act as Threatened, Endangered or Extirpated[1] must identify that species' Critical Habitat, to the extent possible.

DFO's Species at Risk program is responsible for carrying out DFO's mandate under the *Species at Risk Act* (SARA) to protect, recover, and conserve all listed aquatic species at risk in Canada. When an aquatic species is listed on Schedule 1 of SARA as threatened, endangered or extirpated, DFO is required to identify and protect habitat needed for the survival and recovery of the species (Figure 3), which is linked to the population and distribution objectives established in the Recovery Strategy. The identification is based on the best available information (Figure 4). According to SARA, Critical Habitat is defined as "the habitat that is necessary for the survival or recovery of a listed wildlife species". For aquatic species, the Critical Habitat may include areas in the riparian zone.

[1] Species listed as Extirpated under SARA may not require the identification of Critical Habitat unless a program of re-introduction is proposed.

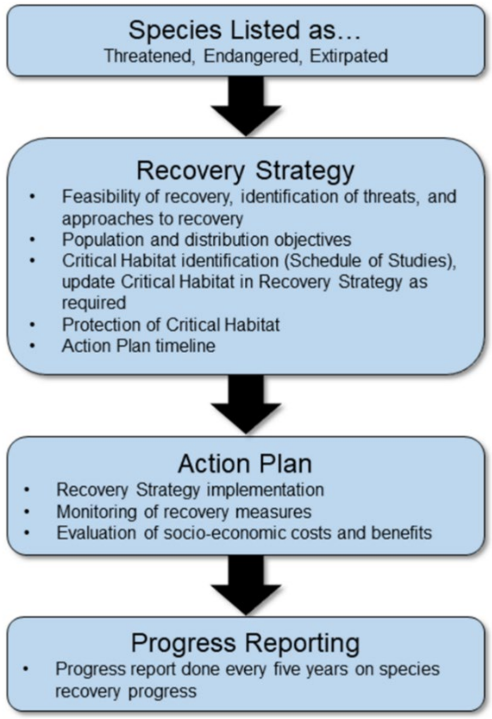

Figure 3: Process followed for protection and recovery of at risk species used by DFO following SARA. Critical Habitat is designated in the Recovery Strategy.

In the DFO (2015) “Guidelines for the identification of Critical Habitat for aquatic species at risk”, riparian zones are defined as features outside the aquatic ecosystem which support the establishment and maintenance of deep and shallow pool features, supply food for migrating and juvenile fish of many species, and influence water temperature (e.g., tree shade). However, as this riparian zone definition is based on the requirements of only a few fish species, it may not represent the features that support most freshwater fishes and mussels’ life cycle processes taking place in Critical Habitat (i.e., functions). Consequently, guidance is required that builds upon and complements the Department’s existing approaches to identify riparian Critical Habitat, in order to make scientifically-defensible decisions about the identification of Critical Habitat in the freshwater riparian zone.

For the purpose of this research document, riparian zone was defined as the area located between a waterbody’s high water mark and the upland area. However, other factors such as groundwater recharge areas that may extend further than the riparian zone but still affect aquatic and/or riparian features may also be considered.

The Species at Risk program has requested advice from DFO Science to ensure a more rigorous and systematic approach to identify Critical Habitat in the riparian zone. The purpose of this research document is to provide guidance on the identification of Critical Habitat in the riparian zone for freshwater species at risk.

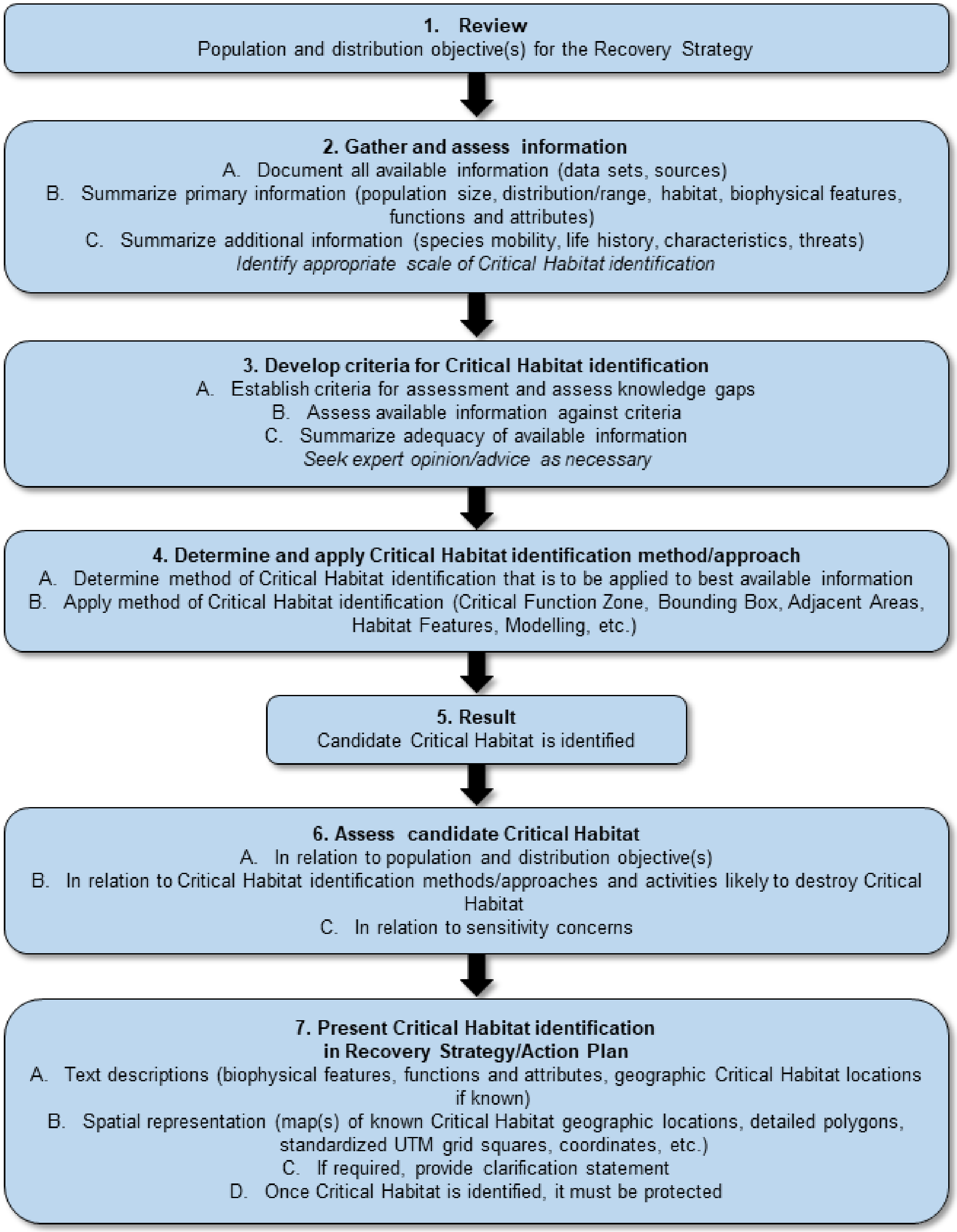

Figure 4: Steps for identification of Critical Habitat of a species or designatable unit of a species for the development of the Recovery Strategy/Action Plan.

The specific objectives are to:

1. Provide guidance on how to determine when riparian features constitute Critical Habitat,

2. Identify the suite of riparian features that provides for freshwater fishes and mussels' functions,
3. Provide, where available, Science Advice on the extent of the riparian zone that is important for features that constitute Critical Habitat, and
4. Present case studies illustrating the use of the guidance for practitioners.

WHEN RIPARIAN HABITAT IS CRITICAL HABITAT

SARA provides protection of the habitat of listed freshwater fishes and mussels since many of the threats to persistence are habitat related, and these habitats will need to be protected to ensure recovery. To determine Critical Habitat, a biophysical description is used. The biophysical elements of Critical Habitat are broken down into: functions, features, and attributes (Figure 5). Functions describe a species' use of habitat and are supported by feature(s) (DFO 2015). Features are the biophysical components of the Critical Habitat that have the capacity to support a function necessary to achieve the species' population and distribution objectives (DFO 2015). Some features designated as Critical Habitat may support functions indirectly by supporting or reinforcing other features (DFO 2015). These features may be outside of the aquatic ecosystem, i.e., in the riparian zones. Every feature is comprised of many attributes, which are the measurable characteristics that enable the feature to support the species' functions (DFO 2015). Attributes provide the greatest level of information about a feature, the quality of the feature, and the mechanism by which the feature is able to support a particular life-cycle requirements of a species (DFO 2015).

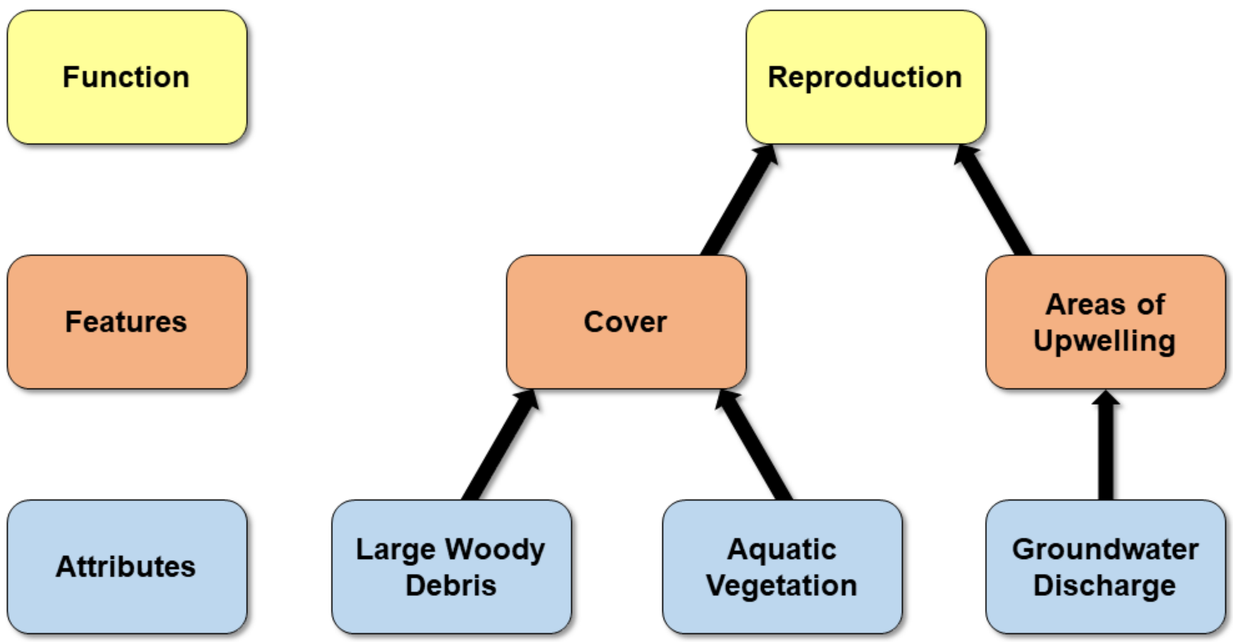

Figure 5: Flow chart representing examples of life-history functions, critical habitat features, and critical habitat attributes.

There is an extensive body of literature outlining the importance of the riparian zone for freshwater aquatic habitats (Pusey and Arthington 2003; Lind et al. 2019), freshwater fishes (Murdoch et al. 2020), and mussels (Zawal et al. 2016). Despite that riparian features clearly support the maintenance of the aquatic habitat, they are not consistently included as Critical

Habitat. For species assessed by COSEWIC as threatened, endangered or extirpated, DFO Science conducts a Recovery Potential Assessment (RPA) in which candidate Critical Habitat may be outlined (Figure 1). This research document contains information to the extent possible to determine the feasibility of recovery of the species (ECCC 2017). The science advice contained in the RPA is used in the development of a Recovery Strategy for species that are deemed to be recoverable (Figure 4). The Recovery Strategy identifies threats to a species or its habitat, defines Critical Habitat to the extent possible, and sets population and distribution objectives for the recovery of the species (ECCC 2017). The process is led by the Species at Risk program (Figure 1).

IDENTIFICATION OF RIPARIAN CRITICAL HABITAT FOR CURRENTLY LISTED SPECIES

Of the 34 RPA reports currently available for freshwater fish and mussel species listed in the SARA registry as threatened, endangered or extirpated, ten mention riparian zones when discussing habitat needs for the species (nine fishes, one mussel). Of the ten species where riparian zones are mentioned, eight were stream or river dwelling and two were lake dwellers. Six RPAs mention ‘riparian habitat’ or ‘riparian vegetation’, while four RPA reports mention specific riparian features/attributes including: woody debris, terrestrial food sources, undercut banks, cover, bank stability, shade, and protection from adjacent land use. The RPA for several species indicated that there was currently a lack of data or understanding when attempting to define candidate Critical Habitat for the species, which may have contributed to the lack of inclusion of riparian zones as candidate Critical Habitat.

Of the available Recovery Strategies for species listed as threatened or endangered, 33 fish species/populations and ten mussel species were found to have Recovery Strategies. Of these, nine fish species (twelve populations) had riparian habitat included as part of their Critical Habitat. Of the nine fish species, five are river dwelling species and four are lake dwelling (seven populations). Four Recovery Strategies only specified riparian habitat to that basic level, while the other eight Recovery Strategies addressed the contributions of riparian habitat to aquatic habitat including: protection of the integrity of other aquatic features such as riffle and shallow pool habitat, large and small woody debris input, localized bank stability, shade to help control instream temperatures, terrestrial insect/food input, limiting added nutrients or contaminants, and maintaining natural channel morphology.

Almost all of the Recovery Strategies we reviewed, including the ones that did not include riparian zones as Critical Habitat, incorporated the loss, damage or reduction of riparian zones as a threat to the species, and included protection or recovery of riparian zones in the recovery planning sections. Taken together, this indicates a need for guidance on how to determine when riparian features constitute Critical Habitat.

HOW TO DETERMINE IF RIPARIAN HABITAT IS CRITICAL HABITAT

Richardson et al. (2010) suggested that riparian habitat should be considered as Critical Habitat if impaired riparian performance affects aquatic habitat quality or water quality in a way that negatively impacts the survival or recovery of a species at risk. Riparian performance is impaired if the riparian features (Figure 6) are not able to support the life-history functions of fishes and mussels. Therefore, riparian features should be considered as Critical Habitat if they are necessary to maintain aquatic habitat or water quality attributes required for the survival or recovery of freshwater fishes and mussels (Figure 7a). If a riparian feature affects aquatic habitat features identified as Critical Habitat, that is a clear path forward for identifying the riparian feature as Critical Habitat (Richardson et al. 2010). Current SARA guidelines on determining Critical Habitat do not provide guidance on how to include water quality as Critical

Habitat (DFO 2015) since water quality isn't a feature but rather a set of attributes common to most aquatic features. In this sense, any riparian feature that affects water quality, in turn affects any aquatic features that would be impaired by poor water quality. However, riparian features located upstream of aquatic Critical Habitat features may influence water flow and quality attributes of aquatic Critical Habitat, and should also be considered when defining riparian Critical Habitat.

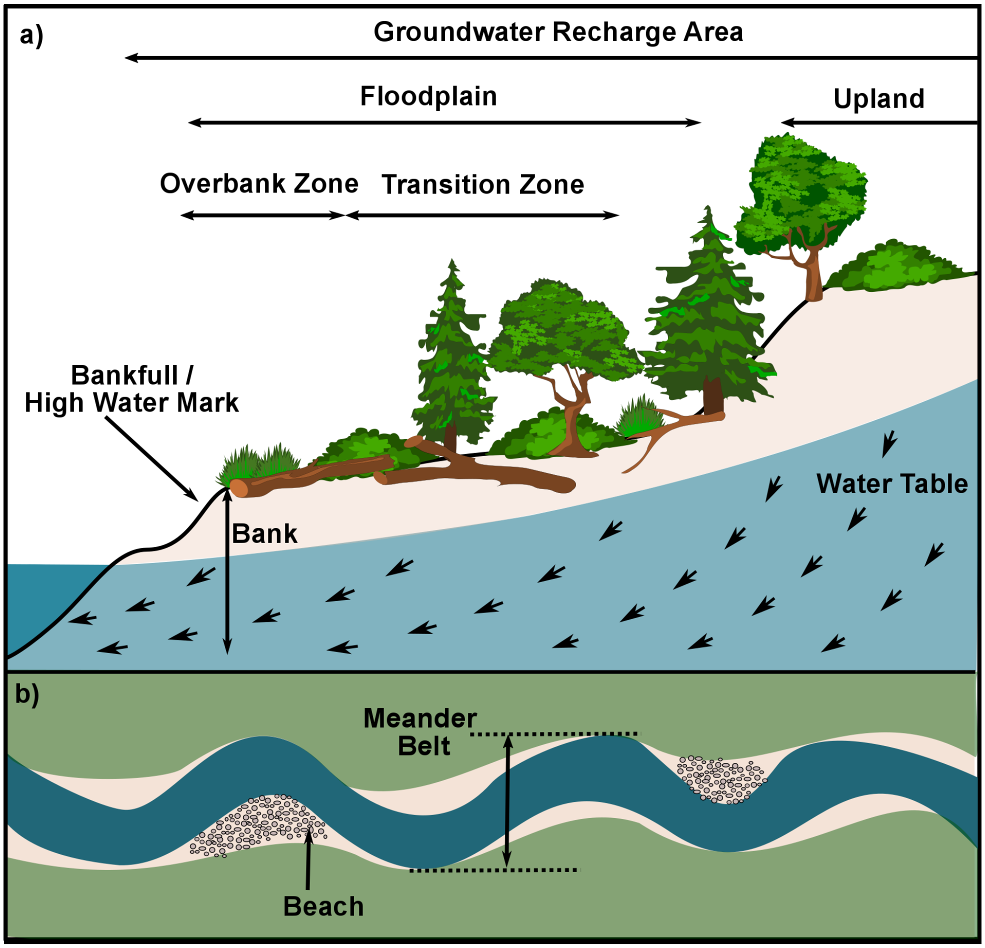

Figure 6: Schematic of riparian features from two different perspectives, cross-sectional (a) and aerial (b).

The boundary between terrestrial and aquatic habitats isn't necessarily a barrier for freshwater fishes and mussels. Due to changes in water level (i.e., flooding), the ability to tolerate desiccation or life-history requirements, riparian features may also directly support the functions of some freshwater fishes or mussels. Riparian features that directly support functions required for the survival or recovery of freshwater fishes and mussels should also be included as Critical Habitat (Figure 7b).

Consequently, we suggest that riparian features are Critical Habitat when they:

1. are necessary to maintain aquatic features identified as Critical Habitat,
2. are necessary to maintain water flow and quality upstream of Critical Habitat; or
3. support functions necessary for the survival or recovery of a listed wildlife species.

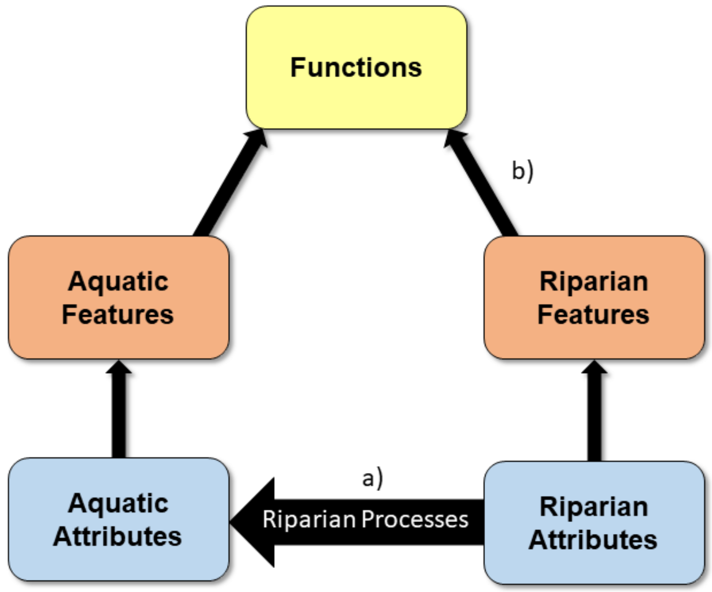

Figure 7: Riparian features can constitute Critical Habitat through a) their indirect effects of riparian processes on aquatic features considered critical habitat or b) through direct effects on a species' functions.

RIPARIAN FEATURES THAT AFFECT AQUATIC HABITAT FEATURES AND WATER QUALITY ATTRIBUTES

The definition of the riparian zone used in this research document is the area located between a waterbody's high water mark and the upland area. The ecosystem in the riparian zone has unique physical, geomorphological, and chemical properties. The riparian ecosystem acts as an interface between aquatic and terrestrial habitats, and is sensitive to environmental change (Naiman and and Décamps 1997). Activities that occur in the riparian zone have direct implications for the aquatic habitat due to the strong connections between aquatic and riparian features.

While there are many nuanced and varied ways that riparian features interact with aquatic features, they do so by the means of a few processes. The seven main processes by which riparian features support aquatic features are: erosion, filtration, infiltration, isolation, meandering, shading, and subsidization (Figure 8). These processes are dynamic and occur within a range of natural of variation that needs to be considered when defining riparian areas as critical habitat.

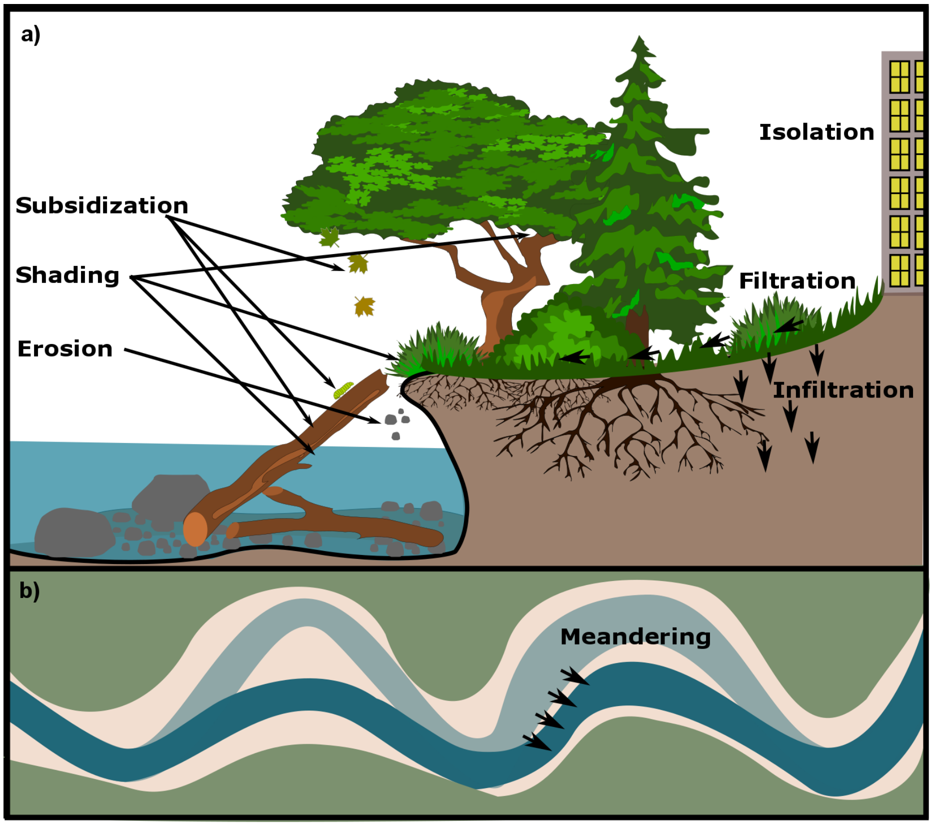

Figure 8: The seven main processes by which features in the riparian zone maintain aquatic features from two different perspectives, cross-sectional (a) and aerial (b).

Erosion

Erosion is the process of soil gradually wearing away by wind, water or gravity. When erosion is occurring within a natural range of variation, it controls sedimentation and siltation; supporting aquatic attributes such as aquatic vegetation and interstitial spaces. Natural levels of erosion prevents contaminants and excess nutrients in the soil of the overbank zone from entering the waterbody (Fox et al. 2016) and maintains water clarity. Controlling sedimentation maintains spaces between coarse sediment, affecting dissolved oxygen levels in the waterbody (Wood and Armitage 1997). These attributes support features such as backwater, cover, eddies, lake benthic habitat, lake littoral habitat, photic environment, riffles, shoals, and wetlands. Erosion in the floodplain is moderated through riparian vegetation by maintaining bank and beach structure (Mondal and Patel 2018).

Filtration

Filtration is the process of removing matter, light or sound from air or water. Filtration prevents contaminants and excess nutrients in surface and subsurface water in the riparian zone from entering a waterbody (Miller et al. 2016; Yu et al. 2019). Riparian vegetation maintains aquatic features such as the acoustic and photic environment by filtering artificial light and sound from the riparian zone and upland areas. When riparian vegetation and soils are maintained in their natural state, their filtration capacity maintains water quality attributes of many aquatic features (Smiley, Jr. et al. 2011; Yu et al. 2019). A lack of contaminants, and maintenance of natural levels of pH and nutrients (i.e., water quality) is an attribute of several aquatic features including:

backwater, cover, eddies, food availability, host species, lake benthic habitat, lake littoral habitat, lake pelagic habitat, migration/movement corridors, and wetlands.

Infiltration

Infiltration is the process by which surface water enters the soil. Riparian vegetation provides shading and structure that prevents evaporation, runoff, and allows surface water in the riparian zone to infiltrate into the water table. Natural levels of infiltration affects the movement of surface and subsurface water into the waterbody thereby maintaining natural flow and water levels. Flow and level directly impact many aquatic habitat features including backwater, cover, eddies, glides, host species, upstream habitat, migration and movement corridors, pools, riffles, runs, shoals, and wetlands.

Infiltration into the soil in the floodplain allows for filtration to occur before contaminants and excess nutrients can enter waterbodies maintaining water quality (National Research Council 2002). The infiltration of surface water in the riparian zone prevents warm water from running off directly into the water body altering water temperature (Herb et al. 2008), recharging groundwater reserves that provide areas of upwelling in waterbodies (Chu et al. 2008). Infiltration can occur over diffuse areas of low infiltration rates or localised areas of high infiltration rates that allow for precipitation to infiltrate the water table quickly.

Isolation

Isolation is the process of causing a place or thing to be distanced from a disturbance. The intensity of noise and light decreases the farther away the source. Therefore, the riparian zone isolates the water body from noise and light pollution that can affect the acoustic and photic environment. Restrictions on human use of a riparian zone can isolate waterbodies from physical disturbances such as trails within the waterbody. The protection of riparian zones from human use (e.g., agriculture and forestry) or development (e.g., mining and road construction) provides isolation from sources of contamination, excess nutrients, and excessive vibrations.

Meandering

Meandering is the process of a stream or river moving back and forth, changing shape as it flows across a floodplain or valley eroding and depositing sediments on alternating banks (Callander 1978). Natural levels of meandering by a river or stream creates habitat features such as cover, backwater, and shoals. Meandering affects flow and level of rivers and streams through the changes in river or stream morphology (DFO et al. 2011). Meandering may also support sympatric speciation through creating barriers to gene flow (Ruzzante et al. 2019).

Shading

Shading is the process of adjusting the amount of light admitted onto a surface. Shading in the aquatic habitat by vegetation, large woody debris (LWD), and undercut banks provides cover (Raines and Miranda 2016; Vargas-Luna et al. 2018) and maintains the photic environment. Shading by riparian vegetation maintains natural variation in temperature of water in the aquatic habitat (Broadmeadow and Nisbet 2004), and of surface and subsurface water in the riparian habitat (Moore et al. 2005).

Subsidization

Subsidization is the process of transferring energy, food, and structural components from the terrestrial habitat to the aquatic habitat. Riparian features provide food for fishes (e.g., terrestrial insects), mussels (e.g., organic matter) and their aquatic prey (e.g., nutrients and organic matter). Nutrient subsidies provide energy and support aquatic vegetation, which provides cover and supports features such as backwater and wetlands. In addition, riparian vegetation and soil subsidies in the aquatic habitat provide sensory cues that may direct fish migration along their migration corridors. Natural riparian vegetation provides carbon, nitrogen, and phosphorus needed for primary production in the aquatic habitat (Brett et al. 2017). Natural weathering of bedrock supplies the calcium pool in catchment soils and riparian vegetation, which is then is exported to waterbodies (Reid et al. 2019).

Coarse sediment, such as gravel and boulders from banks and beaches, in the riparian zone is transferred into waterbodies as a result of erosion processes and meandering. The subsidization of wood, also termed wood recruitment, is the addition of wood into waterbodies from the associated riparian trees as a result of the mortality of individual trees, disturbances affecting multiple trees or meandering of a river or stream (Warren et al. 2009). Wood and coarse sediment subsidization has many roles including creating habitat (e.g., pools), providing cover (e.g., LWD and root wads), and changing channel dynamics in streams and rivers. LWD in rivers can alter flow dynamics reducing the formation of destructive frazil and anchor ice (Nilsson et al. 2013).

THE EFFECT OF RIPARIAN FEATURES ON AQUATIC FEATURES

We performed a literature review to determine current scientific evidence regarding the effect of riparian features on aquatic features and water quality attributes. The literature review was conducted by searching for articles that correspond with a general set of search terms developed to identify articles regarding the effect of the riparian zone on freshwater habitats, and then refined for specific aquatic habitat features from a standardized list of Critical Habitat features and specific aquatic water quality attributes identified in a preliminary search of articles on water quality (Appendix 1). To determine which riparian features may be considered Critical Habitat through their impact on aquatic Critical Habitat features (Figure 7a), their associated processes were outlined for each aquatic feature (Table 1) and water quality attribute (Table 2).

Table 1: The features in the riparian zone that have an effect on aquatic features, and the processes by which these riparian features impact them. The details pertaining to water quality attributes are found in a separate table (Table 2) to reduce redundancies.

Aquatic features	Aquatic attributes	Process	Details	Riparian features	Source(s)
Acoustic environment	sound intensity	filtration, isolation	Riparian features filter out and isolate waterbodies from anthropogenic noise (e.g., road/bridge traffic, urbanization) that can interfere with acoustic signal-to-noise ratios, mask signals or alter organismal behavior.	beach, floodplain	(Mickle and Higgs 2018; Reid et al. 2019)
Areas of upwelling	groundwater discharge	infiltration	Upwelling in the freshwater habitat is caused by groundwater discharge that is recharged in the groundwater recharge area.	floodplain, groundwater recharge area	(Ouellet et al. 2017)
Areas of upwelling	water quality*	-	-	-	-
Backwater	aquatic vegetation	erosion, filtration, subsidization	Aquatic vegetation can reduce flow to create backwater and is supported by the floodplain through control of sedimentation, siltation, water clarity, light, and nutrient inputs.	bank, beach, floodplain	(Cheng and Yong-ming 2008; Jones et al. 2012)
Backwater	-	meandering	Channel migration in the meander belt creates backwater.	meander belt	(Biron et al. 2018)
Backwater	-	erosion	Riparian vegetation maintain banks from eroding and separating backwater from the waterbody.	bank, beach, floodplain	(Mondal and Patel 2018)

Aquatic features	Aquatic attributes	Process	Details	Riparian features	Source(s)
Backwater	large woody debris (LWD)	subsidization	Backwater is created by LWD being recruited from the floodplain.	floodplain	(Lehane et al. 2002; Seo et al. 2010)
Backwater	water quality*	-	-	-	-
Cover	groundwater discharge	infiltration	Upwelling groundwater is recharged in the groundwater recharge area.	floodplain, groundwater recharge area	(Malcolm et al. 2005)
Cover	interstitial spaces	erosion	Vegetation in the floodplain controls erosion, which prevents sedimentation that fills interstitial spaces.	bank, beach, floodplain	(Wohl 2015)
Cover	-	shading, erosion, meandering	Undercut banks are maintained through erosion control in the floodplain and created by meandering in the meander belt.	bank, beach, floodplain, meander belt	(Florsheim et al. 2008; Vargas-Luna et al. 2018)
Cover	LWD	subsidization, shading	LWD in the floodplain provides shading. LWD that falls into the aquatic habitat from the floodplain creates complex habitat and cover.	floodplain	(Crook and Robertson 1999)
Cover	small woody debris	subsidization	Small woody debris that falls into the aquatic habitat from the floodplain creates shelter for juveniles and small-bodied fishes.	floodplain	(Enefalk and Bergman 2016)
Cover	-	shading	Overhanging riparian vegetation in the overbank zone provides cover.	bank, floodplain	(Raines and Miranda 2016)

Aquatic features	Aquatic attributes	Process	Details	Riparian features	Source(s)
Cover	flow and level	infiltration, meandering	Infiltration in the floodplain and meandering in the meander belt affects flow rates and water level which affects the availability of refugia and cover.	floodplain, meander belt	(National Research Council 2002; Logez et al. 2016)
Cover	aquatic vegetation	erosion, filtration, subsidization	Aquatic vegetation provides cover and is supported by the floodplain through control of sedimentation, siltation, water clarity, light, and nutrient inputs.	bank, beach, floodplain	(Jones et al. 2012; Massicotte et al. 2015)
Eddies	aquatic vegetation	erosion, filtration, subsidization	Aquatic vegetation causes swirling and is supported by the floodplain through control of sedimentation, siltation, water clarity, light, and nutrient inputs.	bank, beach, floodplain	(Nepf 2012; Jones et al. 2012)
Eddies	LWD	subsidization	LWD that falls into the aquatic habitat from the terrestrial habitat creates obstacles that create eddies.	floodplain	(Lehane et al. 2002)
Eddies	flow	infiltration, meandering	Infiltration in the floodplain and meandering in the meander belt affects flow rates and water level which affects the flow regimes of eddies.	floodplain, meander belt	(National Research Council 2002)
Eddies	water quality*	-	-	-	-

Aquatic features	Aquatic attributes	Process	Details	Riparian features	Source(s)
Food supply	terrestrial and amphibious prey	subsidization	Terrestrial and amphibious prey species in the floodplain supply food in the aquatic habitat due to incidental use or their life-history requirements.	floodplain	(Albertson et al. 2018)
Food supply	terrestrial organic matter	subsidization	Transfer of organic matter from the floodplain to the aquatic habitat supplies food for freshwater fishes and mussels.	floodplain	(Brett et al. 2017)
Food supply	aquatic insects	subsidization	Some life-history stages of aquatic insects (e.g., adult stage) require use of the floodplain, aquatic insects also need terrestrially sourced nutrients and organic matter.	bank, beach, floodplain	(Harabis 2017)
Food supply	aquatic vegetation	erosion, filtration, subsidization	Aquatic vegetation is supported by the floodplain through control of sedimentation, siltation, water clarity, light, and nutrient inputs.	bank, beach, floodplain	(Jones et al. 2012)
Glides	flow and level	infiltration, meandering	Infiltration in the floodplain and meandering in the meander belt affects flow rates and water level which affects the flow regimes of glides.	floodplain, meander belt	(National Research Council 2002)
Glides	water quality*	-	-	-	-

Aquatic features	Aquatic attributes	Process	Details	Riparian features	Source(s)
Host species (availability of)	water quality	filtration	Terrestrial sources of nitrates filtered by the floodplain affect the ability of mussels to attach to host.	floodplain	(Moore and Bringolf 2018)
Host species (availability of)	flow and level	infiltration, meandering	Infiltration in the floodplain and meandering in the meander belt affects flow rates and water level which affects host attachment by mussels.	floodplain, meander belt	(National Research Council 2002; Modesto et al. 2018)
Upstream habitat	flow and level	infiltration, meandering	Infiltration in the floodplain and meandering in the meander belt affects flow rates and water level which affects upstream habitat.	floodplain, meander belt	(National Research Council 2002)
Upstream habitat	water quality*	-	-	-	-
Lake benthic habitat	sediment	filtration, erosion	Erosion and filtration of contaminants in the floodplain affects sediment quality and quantity in benthic habitat.	bank, beach, floodplain	(Crane 2017)
Lake benthic habitat	water quality*	-	-	-	-
Lake littoral habitat	aquatic vegetation	erosion, filtration, subsidization	Filtration and erosion in the floodplain, and littoral habitat alteration affects the presence of aquatic vegetation in lake littoral habitats.	bank, beach, floodplain	(Doi et al. 2010)
Lake littoral habitat	water quality*	-	-	-	-

Aquatic features	Aquatic attributes	Process	Details	Riparian features	Source(s)
Lake pelagic habitat	water quality*	-	-	-	-
Migration/Movement corridors	sensory cues	subsidization, filtration	Sensory cues that support homing or initiate migration may come from or be disrupted by contaminants from the floodplain.	floodplain	(Scholz et al. 1976)
Migration/Movement corridors	flow and level	infiltration	Infiltration in the floodplain affects flow rates and water level which affects hydrological connections between critical habitats.	floodplain	(Crook et al. 2015)
Migration/Movement corridors	water quality*	-	-	-	-
Photic environment	artificial light	filtration, isolation	Filtration in the floodplain of, and isolation from, light pollution (street lights, houses, etc.) affects parental care behaviour of a fish, timing of migration, and dial movements of prey.	floodplain	(Foster et al. 2016; Reid et al. 2019)
Photic environment	shade	shading	Shading from riparian vegetation, overhanging banks, and LWD in the overbank zone affect the quantity and quality of light in the aquatic habitat.	bank, floodplain	(Pusey and Arthington 2003)

Aquatic features	Aquatic attributes	Process	Details	Riparian features	Source(s)
Photic environment	turbidity	erosion, filtration	Riparian vegetation in the floodplain affects sediment load in the waterbody by control of erosion and filtration of surface water that would otherwise increase turbidity.	bank, beach, floodplain	(Vargas-Luna et al. 2018)
Photic environment	water colour	subsidization, filtration	Lack of browning or greening of water due to filtration of terrestrial nutrient or organic matter in the floodplain affects the photic environment.	floodplain	(Karlsson et al. 2009)
Pools	flow and level	infiltration, meandering	Infiltration in the floodplain and meandering in the meander belt affects flow rates and water level which affects the connectivity of pools in the waterbody.	floodplain, meander belt	(National Research Council 2002)
Pools	LWD	subsidization	The addition of LWD from the floodplain increases the presence of pools in rivers and streams.	floodplain	(Davidson and Eaton 2013)
Pools	water quality*	-	-	-	-
Riffles	exposed coarse sediment	erosion, meandering, subsidization	Erosion control in the floodplain reduces sediment load in the waterbody which maintains exposed coarse sediment. Meandering and erosion of beaches and banks subsidizes coarse sediment.	bank, beach, floodplain	(National Research Council 2002)

Aquatic features	Aquatic attributes	Process	Details	Riparian features	Source(s)
Riffles	flow and level	infiltration, meandering	Infiltration in the floodplain and meandering in the meander belt affects flow rates and water level which affects the production of riffles as they require appropriate flow regimes.	floodplain, meander belt	(National Research Council 2002)
Riffles	LWD	subsidization	The addition of LWD from the floodplain increases the presence of riffles in rivers and streams.	floodplain	(Davidson and Eaton 2013)
Riffles	water quality*	-	-	-	-
Runs	flow and level	infiltration, meandering	Infiltration in the floodplain and meandering in the meander belt affects flow rates and water level which affects the production of runs as they require appropriate flow regimes.	floodplain, meander belt	(National Research Council 2002)
Runs	water quality*	-	-	-	-
Shoals	flow and level	infiltration, meandering	Infiltration in the floodplain and meandering in the meander belt affects flow rates and water level which affects whether the shoal is submerged.	floodplain, meander belt	(National Research Council 2002)

Aquatic features	Aquatic attributes	Process	Details	Riparian features	Source(s)
Shoals	sediment	meandering, erosion	Erosion of banks and beaches, and meandering in the meander belt affects sedimentation in the riparian zone, which can add or remove shoals.	bank, beach, floodplain, meander belt	(National Research Council 2002)
Shoals	water quality*	-	-	-	-
Sympatric species	-	meandering, subsidization	Hierarchical, dendritic, spatially fragmented systems may exhibit high genetic diversity. Allowing natural processes to create dendritic channels and oxbow lakes could support sympatric speciation.	floodplain, meander belt	(Ruzzante et al. 2019)
Wetlands	aquatic vegetation	erosion, filtration, subsidization	Aquatic vegetation is supported by the floodplain through control of sedimentation, siltation, water clarity, light, and nutrient inputs.	bank, beach, floodplain	(National Research Council 2002)
Wetlands	flow and level	infiltration, groundwater discharge	Wetlands are maintained through flow from rivers and streams, groundwater inputs, and run-off from floodplain.	floodplain, groundwater recharge area, meander belt	(National Research Council 2002)
Wetlands	water quality*	-	-	-	-

Table 2: Riparian features and processes that impact water quality attributes.

Aquatic Attributes	Process	Details	Riparian Features	Source(s)
Contaminants	erosion, filtration, infiltration, isolation	Contaminants in surface water and sediments are filtered by riparian vegetation and sediments (through infiltration) in the floodplain and are prevented from entering the aquatic habitat through erosion control and isolation.	bank, beach, floodplain	(Yu et al. 2019; Reid et al. 2019)
Dissolved oxygen	erosion, filtration	Natural levels of dissolved oxygen available to fishes and mussels in a waterbody can be maintained through filtration of nutrient and through control of sedimentation that would otherwise fill interstitial spaces.	bank, beach, floodplain	(Wood and Armitage 1997; Crossman et al. 2019)
Nutrients (P, N, C, Ca)	erosion, filtration, infiltration, subsidization	Erosion, filtration, infiltration, and subsidization in a properly functioning floodplain maintains natural levels of nutrients in waterbodies.	bank, beach, floodplain	(Stutter et al. 2019)
pH	erosion, filtration, infiltration, subsidization	pH buffering capacities of soils affects pH of surface and subsurface water, erosion inputs acidified soils into water, and leaf litter affects aquatic pH.	Bank, beach, floodplain	(Hruška et al. 2001)
Temperature	shading, infiltration	Shading of surface and subsurface water by undercut banks and riparian vegetation in the floodplain, and infiltration that recharges in the groundwater recharge area contributes to maintaining natural water temperature ranges.	bank, beach, floodplain, groundwater recharge area	(Chu et al. 2008; Albertson et al. 2018)

RIPARIAN FEATURES THAT SUPPORT THE FUNCTIONS OF FRESHWATER FISHES AND MUSSELS

The previous section described how riparian features may be considered critical habitat through their impact on aquatic Critical Habitat. Riparian features may also directly provide for the functions of freshwater fishes and mussels (Figure 7b). We performed a literature review to determine the most current scientific evidence regarding the effect of riparian features on the functions of freshwater fishes and mussels. The literature review was performed with a general set of search terms that represent the riparian zone and then refined for specific functions from a standardized list of functions (Glossary, Appendix 1). This review resulted in very few papers, denoting a sparsity of literature; in fact the lack of information on the precise effects of riparian features on the functions of freshwater fishes and mussels has been previously noted (Richardson et al. 2010).

A protected riparian zone supports several functions of freshwater fishes and mussels by making the waterbody more difficult to access, providing isolation from: harvest, introduction of invasive species, and trails and roads that may cross waterbodies and destroy habitat.

The features in the riparian zone directly support feeding and foraging of freshwater fishes or mussels that utilize terrestrial habitats during any part of their life-cycle. This will be species specific, for example fish that deposit eggs on beaches (Martin et al. 2004). Dry floodplains would be considered a riparian feature that directly supports dispersal, reproduction, and rearing for species that utilize this feature during intermittent flooding events (Henning et al. 2006, 2007). Some fishes use banks and beaches to migrate and move past barriers (e.g., eels; Trancart et al. 2018). The availability of terrestrial insects as food would be considered a riparian feature rather than a subsidized aquatic feature if the foraging occurs outside of the aquatic habitat (e.g., insects on riparian vegetation).

DELINEATING PROTECTED AREA IN THE RIPARIAN ZONE

DELINEATION OF RIPARIAN CRITICAL HABITAT FOR CURRENTLY LISTED SPECIES

Ten of the 34 RPAs available for fish and mussel species listed in the SARA registry as threatened or endangered specifically mentioned riparian habitat. In most RPAs, Critical Habitat was not defined spatially, whereas for two species, spatial judgements were made. The RPA for Salish Sucker (*Catostomus* sp.) expressed that a continuous riparian zone with a width of 5–30 m from the top of the bank was required (Pearson 2015). The RPA for Redside Dace (*Clinostomus elongatus*) suggested a width of 30 m adjacent to the meander belt (DFO 2019). The actual determination of spatial areas that contain Critical Habitat, when not specifically defined in the RPA, can be based on Science (in RPAs) or Species at Risk Program's interpretation of an RPA (as for many Great Lakes species).

Several Recovery Strategies provided guidance on how large of a riparian zone should be protected as Critical Habitat, however, there are variations on the extent of protection. For four species of Threespine Stickleback (*Gasterosteus aculeatus*, eight populations), the Recovery Strategies stated that Critical Habitat includes a 15 m riparian width around lakes where the species is found and a 30 m width around stream and marshes connecting these lakes (Fisheries and Oceans Canada 2019a). The Recovery Strategy for the St. Lawrence River population of Striped Bass (*Morone saxatilis*) only indicated the riparian zone under tidal influence as part of Critical Habitat, which is 0–2 m above the water's edge (Fisheries and

Oceans Canada 2019b), while Spotted Gar (*Lepisosteus oculatus*) Critical Habitat covers 'flooded areas' of riparian habitat (Staton et al. 2012). Speckled Dace (*Rhinichthys osculus*) Critical Habitat extends to the high water mark, but no further (Fisheries and Oceans Canada 2018a). Similarly, Carmine Shiner (*Notropis percobromus*) only includes the 'bankful channel width' (Fisheries and Oceans Canada 2013). Finally, the Nooksack Dace (*Rhinichthys cataractae* ssp.) and Salish Sucker Recovery Strategies quantified the size of the riparian zone as all riparian areas on both banks for the entire length of identified aquatic reaches of Critical Habitat (Fisheries and Oceans Canada 2019c, 2019d). For both these species, riparian Critical Habitat is deemed to be continuous and reaches inland from the top of the bank up to a width equal to the widest zone of sensitivity calculated for five riparian features and attributes: LWD, localized bank stability, channel movement, shade, and insect and debris inputs (calculated using methods consistent with those used under the British Columbia Riparian Areas Protection Regulation (Government of British Columbia 2019); i.e., 5–30 m depending on stream characteristics).

Taken together, the large range in recommended widths of riparian protection (0–30 m) in the RPAs and Recovery Strategies signifies the importance of considering the species requirements and the landscape features when recommending Critical Habitat protection in the riparian zone. The inconsistencies between species, and absence of recommendations for many species, may also signify a lack of clarity regarding how far into the riparian zone do riparian Critical Habitat features need to be protected to maintain species' functions.

PROCESSES

When defining Critical Habitat in the Recovery Strategy, it must include a clear description of the geographic area to be protected (DFO 2015). This includes the geographic area representing riparian features that are considered Critical Habitat.

The extent of riparian Critical Habitat protected should be grounded in an empirical understanding of the processes that impact the ability of the riparian zone to support freshwater fishes and mussels' functions. Current literature on these processes and species specific needs must be taken into account to determine the relationship between the amount of habitat protected and its influence on the quality of the aquatic habitat feature of interest. It is also important to consider the shape of the response curve and any dependencies of the attributes of the riparian zone (e.g., slope, land use, soil type) (Gene et al. 2019). Consequently, a single value for the extent of Critical Habitat to be protected will likely not be representative of all species or landscapes. This provides a challenge when developing a national standard.

To provide some context in terms of the information available on extent of habitat, meta-analyses and reviews, along with relevant empirical studies were consulted for each of the processes associated with riparian features. This is by no means a comprehensive summary of all research that has been performed on the topic; which would require a formal meta-analysis that was beyond the scope of this research document. Any values provided below should not be considered targets.

Erosion

The ability of features in the riparian zone to control erosion depends on many factors, however, there is a general consensus that the four main factors to be considered are the riparian attributes: slope, vegetation, soil type, and average annual precipitation (Nigel et al. 2013).

In a field study in the Portneuf region, Quebec, slopes greater than 8% (slope % = rise/run * 100) were found to be prone to erosion, leading the authors to suggest that protection of the entire slope – from the waterbody to the ledge upland – may be required (Nigel et al. 2013). The extent of protection for shallower slopes will depend on the other three factors, i.e., vegetation, sediment, and run-off.

Ratio of root depth to bank height, root density, and surface protection are the three metrics that can be studied to understand the ability of vegetation to control erosion in the floodplain (Rosgen 2001). These metrics must be examined over a sufficient length of the shoreline as connectivity of riparian vegetation affects erosion (Rosgen 2001). The influence of vegetation on erosion is greater the higher the percentage of root depth, root density, and surface protection along the reach. Without vegetation providing sufficient root depth, root density, and surface protection, the erodibility of bank sediments and streamflow will lead to bank instability and erosion (Sweeney and Newbold 2014). Due to the deeper root systems of trees, forested floodplains are thought to provide greater protection from erosion than other vegetation types (Sweeney and Newbold 2014; Rood et al. 2015). However, grasses, which typically have a higher root density than trees, have been shown to be more efficient at preventing erosion than trees on shallower slopes (Lyons et al. 2000).

Sediments that are not compacted and/or contain more clay and organic materials are more resistant to erosion than compacted soils and/or sediments consisting of sand or silt (Blanco and Lal 2010). The water content of the soils also affects erosion, with saturated soils holding less water, leading to more runoff. Larger unstable aggregates of soil are more likely to erode (Blanco and Lal 2010).

Precipitation that flows into surface streams is called runoff. The runoff rate impacts the ability of features in the riparian zone to control erosion. Runoff is affected by meteorological factors (i.e., precipitation) as well as the physical geology and topography of the land. Unusually wet years or disturbances to upland areas will have a greater potential for increased runoff and erosion (Lee et al. 2004). Areas with higher annual rainfall and impervious upland cover (e.g., pavement) may need a greater extent of the riparian zone protected. Resilience to future environmental changes, which may increase the severity and frequency of extreme weather events need to be considered when defining riparian Critical Habitat.

Filtration and Infiltration

Riparian zones diminish the effects of runoff from agriculture and other sources of pollution on the aquatic environment through plant uptake, soil storage, and groundwater mixing. Infiltration of surface water in the floodplain reduces overland flow into waterbodies, thereby minimizing flood events and scouring. As with erosion, floodplains will be most effective at controlling runoff when water flow (overland and subsurface) is evenly distributed and soil infiltration rates are high (e.g., unsaturated sediments that are not compacted or frozen).

Localised areas of high infiltration rates that allow for precipitation to infiltrate the water table rapidly (e.g., cracks in bedrock, macropore flow) can negate the filtration capacity of a riparian zone (Orozco-Lopez et al. 2018). Depressional wetlands and other landscape features that hold water (e.g., dense vegetation) and reduce overland flow are of disproportionally higher importance in the floodplain for increasing filtration and infiltration. In addition, the presence of trees and LWD in the floodplain increases hydraulic roughness, slowing down overland flows and increasing storage capacity; thereby allowing waterbodies to recover quicker from high discharge events (Keeton et al. 2017).

Vegetation in the riparian zone can also act as a barrier to filter out noise and light pollution. Road traffic noise can be reduced by 5 m of moderately dense forest (Ow and Ghosh 2017) acting similar to artificial sound barriers constructed in populated areas.

Process-based model simulations show that the filtration and infiltration of contaminants and excess nutrients from agriculture in the riparian zone depends mainly on vegetation, slope, soil texture, the magnitude of the pollution source, contaminant type, and whether the contaminants are attached to sediment (and the size of the sediment) or dissolved in water (Dosskey et al. 2008). This leads to a wide variety of recommendations for widths. For example, when contaminants are dissolved in water, come from a plentiful source (e.g., a large active farm), and the floodplain is sloped and comprised mainly of clay, then no width would be sufficient for removing contamination or excess nutrients (Dosskey et al. 2008). In contrast, contaminants that are attached to large particles of sediment, come from a weak source, with a flat floodplain comprised of fine soils, then a 100% effectiveness could be achieved at almost any width of riparian zone.

A meta-analysis focused on agricultural lands in Sweden but also included literature from Canada and many other countries, found that riparian zones are 77–100% efficient at filtering sediment at a width of 8.8 m (range: 3.3–18 m, 44 papers), 75–100% effective at filtering nitrogen at 11 m (range: 0.7–30 m, 28 papers), and 75–98% effective at filtering phosphorus at 11 m (range: 4–18 m, 22 papers) (Lind et al. 2019). The variation in efficiency across studies was highly dependent on slope (Lind et al. 2019) and while not shown, most likely also affected by the other environmental conditions on which the filtration ability of the riparian zone depends. The response curve for sediment removal saturated at forest widths of ~30 m in a meta-analysis on forest buffers from Europe, US, and Ontario. However, the response curve for nitrate removal did not appear to saturate below widths of at least 80 m and depended on subsurface flow rates (Sweeney and Newbold 2014).

In many parts of Canada, an additional factor to be considered are limits to filtration and infiltration in the winter and spring when snow is present, grasses are flattened, and the soil is frozen. For example, most studies in landscapes dominated by agriculture regarding the ability of vegetation in the riparian zone to reduce phosphorus concentrations in waterbodies occur in warm or temperate climates (Kieta et al. 2018). A review of studies conducted in cold climates found a very wide range (from -36% to 89%) of phosphorus removal efficiencies of riparian zones that ranged from 5–50 m and comprised mainly of grasses and shrubs (Kieta et al. 2018).

Isolation

Riparian zones can act to isolate the waterbody from: sources of pollution, contaminants, invasive species, and excess nutrients; or from human use (e.g., fishing, trails) and development that can directly impact freshwater fishes and mussels' functions. The harder a waterbody is to get to, the less likely that it will be exploited. For example, the more remote a waterbody, defined by road access or visibility, the less fishing pressure and likelihood of introduction of invasive species (Drake and Mandrak 2014; Kizuka et al. 2014) suggesting that ease of access increases use.

Meandering

The movement of a stream or river across its floodplain is a natural process. The area between the furthest edge of the bends in a meandering river or stream is called the "meander belt" and the natural width of this belt will depend on the slope of the floodplain, channel depth, and presence of erosion-resistant sediments. Natural meandering by a river or stream is unlikely if the slope of the area adjacent to the stream banks is greater than 10%, while slopes less than 4% allow for meandering or braiding (Rosgen 1994). Satellite imagery can be used to determine if the river or stream has evidence of meandering (e.g., oxbow lakes, sinuosity or changes in channel location over time).

Shading

Shading by trees affects water temperature and provides cover. The ability of a forest to regulate water temperature depends on forest width, density, composition, length, and age (Feld et al. 2018). A 30 m forest on either side of the waterbody may protect from temperature increases (Sweeney and Newbold 2014; Feld et al. 2018), and is most effective for streams less than 5 m wide (Feld et al. 2018). The extent of the riparian zone required to maintain undercut banks will depend on erosion and meandering (see above).

Shading leads to a unique microclimate in forested riparian zones with different temperatures and humidity levels than open areas. Soil temperatures in forested riparian zones can be up to 10–15 °C lower under forested canopies during the daytime and 1–2 °C higher at night, likely affecting the temperature of surface and surface water entering waterbodies (Moore et al. 2005). Similarly, it has been speculated that warming of shallow ground water in harvested forests could result in increases water temperatures in streams.

Subsidization

There exists a general understanding of the importance of terrestrial subsidies for freshwater fishes and mussels (Richardson and Sato 2015). Productive riparian floodplains with grasses, trees, and shrubs contribute animals (i.e., insects, amphibians, and small mammals), leaf litter organic matter, pollen, fruits, and seeds to freshwater food webs. In general, subsidies to streams are greater from older, unharvested forests (Richardson and Sato 2015) and the use of terrestrial subsidies by fishes increases with increased aquatic pollution (Kraus et al. 2016).

A meta-analysis focused on agricultural lands in Sweden but included literature from Canada and many other countries, identified the need for a forest of 25 m (range 15–33 m, 4 papers) for insects, and 53 m (range 20–100 m, 6 papers) for amphibians and small mammals (Lind et al. 2019). Subsidies of terrestrial insects are significantly higher in undeveloped lakes (Francis and Schindler 2009) suggesting that development should be limited along lake shorelines to maintain insect subsidies. Transitions in components of the forest ecosystem (e.g., woody debris, leaf litter and hummus composition, and soil chemistry) occurred at around 10–20 m from the edge of streams in the southern Appalachians, which may denote the extent of the forest that interacts strongly with (i.e., subsidizes) the waterbodies studied (Clinton et al. 2010).

It has been suggested that floodplains should be protected to the width equal to ~30 m or the height of mature trees to support wood recruitment (Sweeney and Newbold 2014). There is also evidence that there is more LWD in waterbodies that are surrounded by older forest stands (Lind et al. 2019). Allowing a river to meander can also increase the recruitment of LWD to rivers and streams.

OTHER CONSIDERATIONS

Resilience to natural variation and extreme events

The goal of protecting riparian habitat is to ensure that there is enough area to provide the ecosystem services (i.e., processes) that it provides to the aquatic habitat. That also means maintaining a large enough riparian zone to allow for proper functioning and resilience of riparian features to natural variation and to extreme events. Resilience refers to how likely a system is to change if exposed to pressure, and its ability to recover following a disturbance (DFO 2011). Long term studies may be required to capture any loss of utility of Critical Habitat in the riparian zone due to limited protection. This speaks to the ability of any proposed widths of riparian zones to maintain the terrestrial attributes necessary to support the processes identified.

Natural (site potential) vegetation

Provision of essential processes by riparian Critical Habitat is contingent on the presence of a natural vegetation community typical of the local biogeoclimatic zone. Naturalness refers to how much a system has already been changed, directly or indirectly by human activities (DFO 2011). An altered riparian vegetation community, such as a lawn or cultivated field, may not provide key functional processes like provision of LWD inputs or solar shading. It is therefore implicit in the designation of riparian Critical Habitat that a natural vegetation community be present or if absent, that it be actively or passively restored to an appropriate vegetation community. Passive restoration through natural plant succession may require cessation of any land use activities preventing revegetation (e.g., mowing, grazing, agriculture). The natural target vegetation community can be categorized as the site potential vegetative state, which may range from low ground cover to shrubs to trees, depending on local soil conditions, climate, and moisture availability. It is important to remember that the site potential vegetation is the future potential for the site, and that existing human impacts do not influence the outcome. It should be noted, however, that if permanent infrastructure (rip-rap, buildings) is present in the riparian zone then it may not be possible to restore it to provision of natural biophysical functioning.

Scale

The magnitude of the influence of the riparian habitat on the aquatic habitat depends on the size of the waterbody. Smaller waterbodies (e.g., small streams) may have stronger connections with the riparian habitat than larger waterbodies (e.g., large lakes). However, regulations often scale with waterbody size (e.g., a multiple of channel width), resulting in less protection – in terms of distance from high water mark--for smaller waterbodies. This is due to riparian habitat, in terms of the extent of the terrestrial habitat that interacts directly with the aquatic habitat, scaling with waterbody size (Naiman and Décamps 1997). However, the extent of the riparian zone that directly interacts with the waterbody also depends on the position of the waterbody within a drainage network, the hydraulic regime, and the local geomorphology (Naiman and Décamps 1997). These aspects should be considered when defining riparian Critical Habitat based on waterbody size.

Connectivity

Riparian Critical Habitat will generally need to be located on both sides of the stream adjacent to the aquatic Critical Habitat features that riparian processes support. However, riparian habitat upstream of the identified aquatic Critical Habitat (including non-fish-bearing reaches) may also be identified if the features of upstream riparian habitat are necessary to maintain features of downstream aquatic habitat. This may occur, for example, when lack of upstream riparian habitat results in diminished bank stability and excessive sediment or nutrient inputs that adversely affect downstream aquatic Critical Habitat or when lack of shading affects downstream water quality (e.g., temperature, dissolved oxygen) or contributes to a water quality barrier between aquatic Critical Habitat features. The appropriate length of site-specific upstream riparian Critical Habitat will depend on the process that it supports, local context, and habitat requirement of the listed species. For example, the Recovery Strategy for Vancouver Island Lamprey (*Entosphenus macrostomus*) identified 100 m of upstream riparian habitat on steep spawning streams to maintain bank stability above lamprey spawning sites (MacConnachie and Wade 2016), but appropriate upstream distances could be much longer for temperature regulation (e.g., 2.5 km upstream; (Barton et al. 1985; Cross et al. 2013)).

Upland areas

Performance of the riparian zone is often dependent on the state and use of the upland areas. Although the science advice in this document pertains to Critical Habitat associated with the riparian zone, it is important to note that identifying riparian Critical Habitat will not mitigate threats to upland areas. Some upland areas may also be disproportionately important in maintaining attributes of aquatic Critical Habitat features, and therefore warrant protection. For example, the source of the geothermally heated water for the Liard Hot Springs snail (*Physella wright*) is located far outside what would be considered the riparian zone (Heron 2007). Once identified, the source location may warrant Critical Habitat designation to prevent drilling activities from interrupting the water supply to the hot spring. Similarly, discrete upland (non-riparian) areas may be essential for groundwater recharge or supply of stream base flow during prolonged low-flow periods. Furthermore, identifying Critical Habitat in the riparian zone or even upland areas, is not a substitute to adequately managing land use at the broader scale.

Host species

Under the current SARA guidelines, the availability of a host species is a considered Critical Habitat feature when necessary for the survival, recovery, and resilience of a SARA listed species. SARA does not, however, consider the habitat that supports the host as Critical Habitat. Activities occurring outside the identified critical habitat that reduce the availability of hosts inside the Critical Habitat may be considered an activity likely to destroy Critical Habitat. This may be an oversite; we feel that the inclusion of the habitat of the host species as Critical Habitat should be considered on a case-by case basis. If availability of a host species is limiting the survival or recovery of a listed species, then the habitat of the host species may also need to be considered Critical Habitat

Uncertainties

There are inherent uncertainties in the advice outlined above. Meta-analyses may provide more precise width recommendations than individual studies, and an examination of heterogeneity that many individual studies are not able to provide. However, even meta-analyses are not able to capture the range of climates encountered across Canada, tend to be limited in scope to a certain type of land use (e.g., agriculture), and due to their inclusion requirements may be limited to short-term studies. Many of the reviews and meta-analyses included above were performed in agricultural areas; because of this, there was more information regarding erosion, filtration, and infiltration than there was for isolation, meandering, shading or subsidization.

Additional resources

When defining the geographic area to be protected, additional resources may be required to determine the slope, sediment, and land cover in the area occupied by the listed species. In addition, it is important to consider the provincial guidelines for protecting riparian zones around waterbodies.

Slope data

GIS information can be downloaded or requested from the following databases:

Natural Resources Canada - Topographic Information

Government of Canada – Geospatial Data Extraction

Soil data

GIS information can be downloaded or requested from the following databases:

Canadian Soil Information Service

Government of Canada – Open Government – Detailed Soil Survey

Government of Canada – Open Government – Soils of Canada, Derived

Natural Resources Canada – Canadian Forest Service Publications: Digital mapping of soil properties in Canadian managed forests at 250 m of resolution using the k-nearest neighbor method.

Land cover data

GIS information can be downloaded or requested from the following database:

Government of Canada – Open Government – 2015 Land Cover of Canada

Provincial guidelines

When identifying Critical Habitat for SARA listed species, biologists and managers work with the provinces where the populations are located. Provinces maintain their own regulations regarding riparian habitat for the protection of waterbodies from land use practices. We reviewed existing provincial regulations, guidance, and best-practice documents and have compiled a list of those reviewed to show the differences across the country (Appendix 2). The SARA program is required to consult with the respective province on Critical Habitat designation, and often works closely with provincial regulators to establish protected zones using current provincial regulations.

CASE STUDIES

Not all species will be equally affected by the riparian zone. For example, species that are not sensitive to water quality, prefer turbid, warm waters, and live in the pelagic zone of a large lake, probably require less riparian Critical Habitat. As habitat requirements differ between species and ecosystems, the delineation of riparian Critical Habitat should be species- and site-specific and is best evaluated by species experts based on the biology of individual species using knowledge of the local landscape.

In this final chapter, we present five case studies using Mapleleaf (*Quadrula quadrula*), Redside Dace (*Clinostomus elongatus*), Salish Sucker (*Catostomus sp.*), Spring Cisco (*Coregonus sp.*), and Westslope Cutthroat Trout (*Oncorhynchus clarkii lewisi*) to illustrate the use of the guidance developed in this report. These case studies are by no means to be considered as a replacement for the current Critical Habitat designation.

MAPLELEAF

Mapleleaf, a freshwater mussel, is found in Canadian waters in parts of Manitoba and Ontario and are separated into two designatable units (DU): the Great Lakes – Upper St. Lawrence DU in Ontario and the Saskatchewan – Nelson River DU in Manitoba. In 2016, the Great Lakes – Upper St. Lawrence DU was downlisted from threatened status to special concern status and the Saskatchewan – Nelson River DU was downlisted from endangered status to threatened status (Fisheries and Oceans Canada 2018b). Mapleleaf requires a host species, Channel Catfish (*Ictalurus punctatus*), as part of the reproduction and development life stage.

Mapleleaf requires wetlands and runs in medium to large rivers with slow to fast flow and substrates of coarse gravel, fine gravel, sand, clay/mud mixtures, and/or mud. Water quality attributes required for survival include low contaminant levels, dissolved oxygen levels above >4 $mg \cdot l^{-1}$, and water temperatures between 0–27 °C (Table 5). A supply of plankton, including organic detritus and protozoans, is required for adult and juvenile food sources (Fisheries and Oceans Canada 2018b).

The host species, Channel Catfish require similar habitat to the Mapleleaf, generally living in streams with moderate to swift flow, with gravel, rubble, sand or mud bottoms. Channel Catfish spend the majority of their time in a residence found in holes or under cover such as sunken logs, undercut banks or rocks and also males use these areas to build a nest, which they defend during spawning. Terrestrial insects and vegetation are often sources of food for both Channel Catfish and the fish species that they prey upon. Channel Catfish is abundant and widely distributed. Consequently, their availability should not be limiting to the Mapleleaf.

The processes required to support the Critical Habitat features to support Mapleleaf include erosion, filtration, subsidization, infiltration, groundwater discharge, and meandering (Table 1). To support these processes, Critical Habitat needs to include the riparian habitat features floodplain, meander belt, bank, and recharge areas adjacent to aquatic Critical Habitat (Table 3). In addition, banks, beaches, and floodplains adjacent to upstream habitat may need to be protected to maintain the water quality and flow of aquatic Critical Habitat.

Table 3: Guidance for riparian Critical Habitat designation for Mapleleaf.

Aquatic Features	Aquatic Attributes	Processes	Riparian Features
Food supply	aquatic vegetation, leaf litter	filtration, subsidization	bank, floodplain
Runs	flow and level, coarse sediment, water quality*	erosion, infiltration, meandering, subsidization	bank, floodplain, meander belt
Upstream habitat	flow and level, water quality*	meandering, infiltration	floodplain, meander belt
Wetlands	aquatic vegetation, flow and level, water quality*	erosion, filtration, infiltration, subsidization	bank, floodplain, meander belt, groundwater recharge area
Water Quality Attributes*			
	contaminants, dissolved oxygen, nutrients, pH, temperature	erosion, filtration, infiltration, isolation, subsidization	bank, floodplain

REDSIDE DACE

Redside Dace requires pools, riffles, and areas of upwelling as Critical Habitat features to support functions necessary for the survival of the species (DFO 2019). The maintenance of these Critical Habitat features require erosion, infiltration, meandering, shading, and subsidization (Table 1). In addition, Redside Dace have specific requirements for water quality attributes including clear water <24 °C with dissolved oxygen >7 $mg \cdot l^{-1}$ (DFO 2019). To maintain these water quality attributes, the additional process of filtration is required (Table 1).

Redside Dace occurs in streams that are prone to the process of meandering. Current empirical evidence suggests that to enable meandering to occur, the width of the meander belt should be considered Critical Habitat (Table 4). Beyond the meander belt, the slope, sediment, and vegetation in the remaining floodplain will determine the extent of the riparian features to be considered Critical Habitat. Features that hold water and allow for infiltration (e.g., dense vegetation, wetlands) within the groundwater recharge area should be considered Critical Habitat to maintain areas of upwelling. The bank, beach, floodplain, and meander belt upstream of aquatic Critical Habitat, may also be considered Critical Habitat to protect water quality and flow of aquatic Critical Habitat. Finally, the meander belt and floodplain adjacent to migration and movement corridors connecting aquatic Critical Habitat may need protection to ensure water quality and flow.

Table 4: Guidance for riparian Critical Habitat designation for Redside Dace.

Aquatic Features	Aquatic Attributes	Processes	Riparian Features
Areas of upwelling	groundwater discharge, water quality*	infiltration	floodplain, groundwater recharge area
Cover	LWD, overhanging riparian vegetation, undercut banks, water quality*	erosion, meandering, shading, subsidization	bank, floodplain
Food supply	terrestrial insects	subsidization	floodplain
Movement/ migration corridors	flow and level, water quality*	infiltration, meandering	floodplain, meander belt
Pools	flow and level, LWD, water quality*	infiltration, meandering, subsidization	floodplain, meander belt
Riffles	exposed coarse sediment, flow and level, LWD, water quality*	erosion, infiltration, meandering, subsidization	floodplain, meander belt
Upstream habitat	flow and level, water quality*	filtration, infiltration	floodplain

Aquatic Features	Aquatic Attributes	Processes	Riparian Features
Wetlands	flow and level, water quality*	infiltration	floodplain, groundwater recharge areas
Water Quality Attributes*			
	dissolved oxygen, temperature, turbidity	erosion, infiltration, meandering, shading	bank, beach, floodplain, meander belt

SALISH SUCKER

The Salish Sucker is a small bodied freshwater fish that is found in low elevation, meandering headwater streams, sloughs, marshes and beaver ponds in eleven watersheds in the Fraser Valley between Surrey and Chilliwack in southern British Columbia (Fisheries and Oceans Canada, 2019d). Salish Sucker require a mixture of shallow and deep pools, riffles, and glides as habitat to support all of their life stages. Connectivity of these aquatic habitats is important, as different life stages make use of different habitat types. Riffle habitat with water depths of more than 70 cm is used for spawning, and populations that do not have riffle habitat near their marsh or pond have been known to travel long distances in order to find suitable riffle habitat for spawning. Shallow pools and glides are used as nursery and rearing habitat by young-of-the-year Salish Sucker, while juvenile and adults are most often found in the deep pool habitat (pools deeper than 70 cm). Adequate dissolved oxygen levels (≥ 4 mg·l^{-1}), water temperatures between 6 and 23 °C and low levels of sediment, nutrients and toxins are required in all aquatic Critical Habitat to support survival of Salish Sucker.

Riparian habitat has been identified as Critical Habitat for Salish Sucker in the Recovery Strategy (Fisheries and Oceans Canada, 2019d), specifically a continuous strip of native vegetation along the entire length of aquatic Critical Habitat. All seven of the processes provided by riparian habitat are required by Salish Sucker, with erosion, infiltration, filtration, and isolation providing protection to water quality attributes from agricultural runoff and sedimentation from residential land development, subsidization providing LWD for the formation of pools and is a source of terrestrial insects, a major food source of adult, juvenile, and young-of-the-year fish, shading providing cover and temperature control, and meandering causing additions of LWD and the formation of cover and pools (Table 5).

Table 5: Guidance for riparian Critical Habitat designation for Salish Sucker

Aquatic Features	Aquatic Attributes	Processes	Riparian Features
Pool	flow and level, LWD, water quality*	infiltration, meandering, subsidization	floodplain, meander belt
Riffle	exposed coarse sediment, flow and level, LWD, water quality*	erosion, infiltration, meandering, subsidization	bank, beach, floodplain, meander belt
Glide	flow, water quality*	infiltration, meandering	floodplain, meander belt
Cover	aquatic vegetation, interstitial spaces, flow and level, LWD, small woody debris, water quality*	erosion, filtration, infiltration, meandering, recruitment, shading, subsidization	floodplain, bank, meander belt, beach,
Food supply	terrestrial prey, aquatic insects	subsidization	bank, beach, floodplain
Migration /movement corridors	sensory cues, flow and level, water quality*	filtration, infiltration, subsidization,	floodplain
Photic environment	turbidity, shade	erosion, filtration, shading	bank, beach, floodplain
Upstream habitat	flow and level, water quality*	filtration, infiltration	floodplain
Water Quality Attributes*			
	contaminants, dissolved oxygen, nutrients, temperature	erosion, filtration, infiltration, isolation, shading, subsidization	bank, beach, floodplain, groundwater recharge area

SPRING CISCO

Spring Cisco is endemic to Lac des Écorces in Quebec and therefore the entire lake has been deemed Critical Habitat for this species (DFO 2014). Spring Cisco require cool, well oxygenated water, especially while spawning (i.e., <6 °C), and appear to make vertical migrations into the deeper areas of the lake to regulate temperature (DFO 2010). Erosion has been observed at Lac des Écorces leading to sedimentation of the benthic habitat in the lake (DFO 2010). The removal of riparian vegetation by residents and contamination from waste water and agricultural run-off were identified as important primary threats for Spring Cisco (DFO 2010).

Preserving habitat quality in the benthic habitat is crucial for the survival of Spring Cisco (DFO 2010). For erosion, additional protection may be required for riparian features depending on the slope and sediment (Table 6). According to the topographic map, changes in elevation of 60 m can occur in as little as 100 m from the shoreline, suggesting that some areas around the lake will have very steep slopes and protection should extend to the upland edge of the floodplain in these areas. To enable shading by trees 30 m from the high water mark may be considered Critical Habitat, however, the impact of shading by trees may not significantly contribute to the temperature of a lake of this size. In addition, the riparian zones adjacent to tributaries of the lake (i.e., upstream habitat) which are not currently considered aquatic Critical Habitat for Spring Cisco, may also need to be considered riparian Critical Habitat.

Table 6: Guidance for riparian Critical Habitat designation for Spring Cisco.

Aquatic Features	Aquatic Attributes	Processes	Riparian Features
Lake benthic habitat	sediment, water quality*	erosion	bank, beach, floodplain
Upstream habitat	flow, water quality*	infiltration	floodplain
Water Quality Attributes*			
	dissolved oxygen	erosion, filtration	bank, beach, floodplain
	temperature	shading, infiltration	floodplain
	contaminants	erosion, filtration, infiltration, isolation	bank, beach, floodplain
	nutrients (P, N, C, Ca)	erosion, filtration, infiltration, subsidization	bank, beach, floodplain

WESTSLOPE CUTTHROAT TROUT

Westslope Cutthroat Trout requires a multitude of aquatic habitat features including river and stream segments that are comprised of riffle, run, pool, and backwater features for stream-resident populations and lakes for adfluvial populations (COSEWIC, 2016). The maintenance of these aquatic habitat features require erosion, infiltration, meandering, shading, and subsidization (Table 1). In addition, Westslope Cutthroat Trout have specific requirements for water quality attributes including clear, cool, aerated water (Fisheries and Oceans Canada 2019e). To maintain these water quality attributes, the additional process of filtration is required (Table 1).

Westslope Cutthroat Trout occur in headwater streams that are subject to meandering processes to lesser extent than Redside Dace, but stream meandering still occurs. Consequently, given the scientific evidence, this suggests the width of the meander belt should be considered as Critical Habitat (Table 7). Due to its mountainous habitat, for Westslope Cutthroat Trout, slope in the remaining floodplain will determine the extent of the riparian features to be considered Critical Habitat, with sediment and vegetation playing lesser roles. Where slope is greater than 8%, the entire floodplain to the upland ledge will need to be protected to control erosion. Features that hold water and allow for infiltration (e.g., dense vegetation, wetlands) within the groundwater recharge area should be considered Critical Habitat to maintain areas of upwelling. In addition, riparian features adjacent to upstream habitat of aquatic Critical Habitat may be considered Critical Habitat to protect water quality, level, and flow. Finally, riparian habitat adjacent to migration and movement corridors connecting aquatic Critical Habitat may need protection to ensure water quality and flow.

Table 7: Guidance for riparian Critical Habitat designation for Westslope Cutthroat Trout

Aquatic Features	Aquatic Attributes	Processes	Riparian Features
Areas of upwelling	groundwater discharge, water quality*	infiltration	floodplain, groundwater recharge area
Backwater	structure, water quality*	erosion, meandering	bank, floodplain, meander belt
Cover	LWD, undercut banks, overhanging riparian vegetation. water quality*	erosion, meandering, shading, subsidization	floodplain, meander belt
Food supply	terrestrial insects	subsidization	floodplain
Migration/movement corridors	flow and level, water quality*	infiltration	floodplain
Pools	flow and level, LWD, water quality*	infiltration, meandering, subsidization	floodplain, meander belt

Aquatic Features	Aquatic Attributes	Processes	Riparian Features
Riffles	exposed coarse sediment, flow and level, LWD, water quality*	erosion, meandering, subsidization	bank, floodplain, meander belt
Upstream habitat	flow and level, water quality*	infiltration, meandering	floodplain, meander belt
Water Quality Attributes*			
	dissolved oxygen, temperature, turbidity	erosion, filtration, infiltration, groundwater discharge, meandering, shading	bank, floodplain, groundwater recharge area, meander belt

REFERENCES CITED

Albertson, L.K., Ouellet, V., and Daniels, M.D. 2018. Impacts of stream riparian buffer land use on water temperature and food availability for fish. J. Freshw. Ecol. **33**(1): 195–210. doi:10.1080/02705060.2017.1422558.

Barton, D.R., Taylor, W.D., and Biette, R.M. 1985. Dimensions of riparian buffer strips required to maintain trout habitat in southern Ontario streams. **5**: 365–378.

Biron, P.M., Buffin-Bélanger, T., and Massé, S. 2018. The need for river management and stream restoration practices to integrate hydrogeomorphology: Stream restoration and hydrogeomorphology. Can. Geogr. Géographe Can. **62**(2): 288–295. doi:10.1111/cag.12407.

Blanco, H., and Lal, R. 2010. Principles of soil conservation and management. Springer, Dordrecht.

Brett, M.T., Bunn, S.E., Chandra, S., Galloway, A.W.E., Guo, F., Kainz, M.J., Kankaala, P., Lau, D.C.P., Moulton, T.P., Power, M.E., Rasmussen, J.B., Taipale, S.J., Thorp, J.H., and Wehr, J.D. 2017. How important are terrestrial organic carbon inputs for secondary production in freshwater ecosystems? Freshw. Biol. **62**(5): 833–853. doi:10.1111/fwb.12909.

Broadmeadow, S., and Nisbet, T.R. 2004. The effects of riparian forest management on the freshwater environment: a literature review of best management practice. Hydrol. Earth Syst. Sci. **8**(3): 286–305. doi:10.5194/hess-8-286-2004.

Callander, R.A. 1978. River meandering. Annu. Rev. Fluid Mech. **10**: 129–158. doi:10.1146/annurev.fl.10.010178.001021.

Cheng, L., and Yong-ming, S. 2008. Flow structure and sediment transport with impacts of aquatic vegetation. J. Hydrodyn. **20**(4): 461–468. doi:10.1016/S1001-6058(08)60081-5.

Chu, C., Jones, N.E., Mandrak, N.E., Piggott, A.R., and Minns, C.K. 2008. The influence of air temperature, groundwater discharge, and climate change on the thermal diversity of stream fishes in southern Ontario watersheds. Can. J. Fish. Aquat. Sci. **65**(2): 297–308. doi:10.1139/F08-007.

Clinton, B.D., Vose, J.M., Knoepp, J.D., Elliott, K.J., Reynolds, B.C., and Zarnoch, S.J. 2010. Can structural and functional characteristics be used to identify riparian zone width in southern Appalachian headwater catchments? Can. J. For. Res. **40**(2): 235–253. doi:10.1139/X09-182.

Collaboration for Environmental Evidence. 2018. Guidelines and standards for evidence synthesis in environmental management. Version 5.0. Available from www.environmentalevidence.org/information-for-authors.

Crane, J.L. 2017. Ambient sediment quality conditions in Minnesota lakes, USA: Effects of watershed parameters and aquatic health implications. Sci. Total Environ. **607**: 1320–1338. doi:10.1016/j.scitotenv.2017.05.241.

Crook, D.A., Lowe, W.H., Allendorf, F.W., Eros, T., Finn, D.S., Gillanders, B.M., Hadweng, W.L., Harrod, C., Hermoso, V., Jennings, S., Kilada, R.W., Nagelkerken, I., Hansen, M.M., Page, T.J., Riginos, C., Fry, B., and Hughes, J.M. 2015. Human effects on ecological connectivity in aquatic ecosystems: Integrating scientific approaches to support management and mitigation. Sci. Total Environ. **534**: 52–64. doi:10.1016/j.scitotenv.2015.04.034.

Crook, D.A., and Robertson, A.I. 1999. Relationships between riverine fish and woody debris: implications for lowland rivers. Mar. Freshw. Res. **50**: 941–953. doi:10.1071/MF99072.

Cross, B.K., Bozek, M.A., and Mitro, M.G. 2013. Influences of Riparian Vegetation on Trout Stream Temperatures in Central Wisconsin. N. Am. J. Fish. Manag. **33**(4): 682-692. doi:10.1080/02755947.2013.785989.

Crossman, J., Futter, M.N., Elliott, J.A., Whitehead, P.G., Jin, L., and Dillon, P.J. 2019. Optimizing land management strategies for maximum improvements in lake dissolved oxygen concentrations. Sci. Total Environ. **652**: 382–397. doi:10.1016/j.scitotenv.2018.10.160.

Davidson, S.L., and Eaton, B.C. 2013. Modeling channel morphodynamic response to variations in large wood: Implications for stream rehabilitation in degraded watersheds. Geomorphology **202**(SI): 59–73. doi:10.1016/j.geomorph.2012.10.005.

DFO. 2010. Recovery Potential Assessment for Spring Cisco (*Coregonus sp.*). DFO Can. Sci. Advis. Sec. Science adv. Rep.

DFO. 2011. Ecologically and biologically significant areas – lessons learned. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep.

DFO. 2014. Recovery strategy for the Spring Cisco (*Coregonus sp.*). Recovery Strategy Series of the Species at Risk Act, Fisheries and Oceans Canada, Ottawa.

DFO. 2015. Guidelines for the identification of Critical Habitat for aquatic species at risk. Fisheries and Oceans Canada.

DFO. 2019. Recovery Potential Assessment of Redside Dace (*Clinostomus elongatus*) in Canada. Can. Sci. Advis. Sec. Res. Doc., DFO.

Dosskey, M.G., Helmers, M.J., and Eisenhauer, D.E. 2008. A design aid for determining width of filter strips. J. Soil Water Conserv. **63**(4): 232–241. doi:10.2489/jswc.63.4.232.

Drake, D.A.R., and Mandrak, N.E. 2014. Bycatch, bait, anglers, and roads: Quantifying vector activity and propagule introduction risk across lake ecosystems. Ecol. Appl. **24**(4): 877–894. doi:10.1890/13-0541.1.

ECCC. 2017. SARA Annual Report for 2017 Species at Risk Act. Environment and Climate Change Canada. Available from https://www.canada.ca/en/environment-climate-change/services/species-risk-public-registry/publications/annual-report-2017.html.

Enefalk, A., and Bergman, E. 2016. Effect of fine wood on juvenile Brown Trout behaviour in experimental stream channels. Ecol. Freshw. Fish **25**(4): 664–673. doi:10.1111/eff.12244.

Faber-Langendoen, D., Keeler-Wolf, T., Meidinger, D., Josse, C., Tart, D., Navarro, G., Hoagland, B., Ponomarenko, S., Saucier, J.-P., Fults, G., and Helmer, E. 2012. Classification and description of world formation types. Part II (Description of formation types). Hierarchy Revisions Working Group, Federal Geographic Data Committee, FGDC Secretariat, U.S. Geological Survey. Reston, VA, and NatureServe, Arlington, VA.

Feld, C.K., Birk, S., Bradley, D.C., Hering, D., Kail, J., Marzin, A., Melcher, A., Nemitz, D., Pedersen, M.L., Pletterbauer, F., Pont, D., Verdonschot, P.F.M., and Friberg, N. 2011. From natural to degraded rivers and back again: A test of restoration ecology theory and practice. *In* Advances in Ecological Research. *Edited by* Woodward, G. pp. 119–209.

Feld, C.K., Fernandes, M.R., Ferreira, M.T., Hering, D. ormerod, S.J., Venohr, M., and Gutiérrez-Cánovas, C. 2018. Evaluating riparian solutions to multiple stressor problems in river ecosystems - A conceptual study. Water Res. **139**: 381–394. doi:10.1016/j.watres.2018.04.014.

Fisheries and Oceans Canada. 2013. Recovery Strategy for the Carmine Shiner (*Notropis percobromus*) in Canada. Fisheries and Oceans Canada, Ottawa.

Fisheries and Oceans Canada. 2018a. Recovery Strategy for the Speckled Dace (*Rhinichthys osculus*) in Canada. Ottawa.

Fisheries and Oceans Canada. 2018b. Recovery Strategy and action plan for the Mapleleaf (*Quadrula quadrula*) in Canada (Great Lakes-Upper St. Lawrence population) [Proposed]. Fisheries and Oceans Canada, Ottawa.

Fisheries and Oceans Canada. 2019a. Recovery Strategy for Paxton Lake, Enos Lake, and Vananda Creek Stickleback species pairs (*Gasterosteus aculeatus*) in Canada. Fisheries and Oceans Canada, Ottawa.

Fisheries and Oceans Canada. 2019b. Recovery Strategy and Action Plan for the Striped Bass (*Morone saxatilis*), St. Lawrence River population, in Canada [Proposed]. Fisheries and Oceans Canada, Ottawa.

Fisheries and Oceans Canada. 2019c. Recovery Strategy for the Nooksack Dace (*Rhinichthys cataractae ssp.*) in Canada [Proposed]. 1st amendment. Fisheries and Oceans Canada, Ottawa.

Fisheries and Oceans Canada. 2019d. Recovery Strategy for the Salish Sucker (*Catostomus sp. cf. catostomus*) in Canada [Proposed]. 1st amendment. Fisheries and Oceans Canada, Ottawa.

Fisheries and Oceans Canada. 2019e. Recovery strategy and action plan for the Westslope Cutthroat Trout (*Oncorhynchus clarkii lewisi*) Alberta population (also known as Saskatchewan-Nelson River populations) in Canada. Fisheries and Oceans Canada.

Florsheim, J.L., Mount, J.F., and Chin, A. 2008. Bank erosion as a desirable attribute of rivers. BioScience **58**(6): 519–529. doi:10.1641/B580608.

Foster, J.G., Algera, D.A., Brownscombe, J.W., Zolderdo, A.J., and Cooke, S.J. 2016. Consequences of different types of littoral zone light pollution on the parental care behaviour of a freshwater teleost fish. Water. Air. Soil Pollut. **227**: 404. doi:10.1007/s11270-016-3106-6.

Fox, G.A., Purvis, R.A., and Penn, C.J. 2016. Streambanks: A net source of sediment and phosphorus to streams and rivers. J. Environ. Manage. **181**: 602–614. doi:10.1016/j.jenvman.2016.06.071.

Francis, T.B., and Schindler, D.E. 2009. Shoreline urbanization reduces terrestrial insect subsidies to fishes in North American lakes. Oikos **118**(12): 1872–1882. doi:10.1111/j.1600-0706.2009.17723.x.

Gene, S.M., Hoekstra, P.F., Hannam, C., White, M., Truman, C., Hanson, M.L., and Prosser, R.S. 2019. The role of vegetated buffers in agriculture and their regulation across Canada and the United States. J. Environ. Manage. **243**: 12–21. doi:10.1016/j.jenvman.2019.05.003.

Government of British Columbia. 2019. Riparian areas protection regulation. Available from http://canlii.ca/t/53pnx.

Harabis, F. 2017. Does the management of surrounding terrestrial habitats increase the tendency of odonates to leave aquatic habitats? Biodivers. Conserv. **26**(9): 2155–2167. doi:10.1007/s10531-017-1350-8.

Henning, J.A., Gresswell, R.E., and Fleming, I.A. 2006. Juvenile salmonid use of freshwater emergent wetlands in the floodplain and its implications for conservation management. North Am. J. Fish. Manag. **26**(2): 367–376. doi:10.1577/M05-057.1.

Henning, J.A., Gresswell, R.E., and Fleming, I.A. 2007. Use of seasonal freshwater wetlands by fishes in a temperate river floodplain. J. Fish Biol. **71**(2): 476–492. doi:10.1111/j.1095-8649.2007.01503.x.

Herb, W.R., Janke, B., Mohseni, O., and Stefan, H.G. 2008. Thermal pollution of streams by runoff from paved surfaces. Hydrol. Process. **22**(7): 987–999. doi:10.1002/hyp.6986.

Heron, J. 2007. Recovery Strategy for the Hotwater Physa (*Physella wrighti*) in Canada. Fisheries and Oceans Canada, Ottawa.

Hruška, J., Laudon, H., Johnson, C.E., Köhler, S., and Bishop, K. 2001. Acid/base character of organic acids in a boreal stream during snowmelt. Water Resour. Res. **37**(4): 1043–1056. doi:10.1029/2000WR900290.

Jones, J.I., Collins, A.L., Naden, P.S., and Sear, D.A. 2012. The relationship between fine sediment and macrophytes in rivers. Riv. Res. Appl. **28**(7): 1006–1018. doi:10.1002/rra.1486.

Karlsson, J., Bystrom, P., Ask, J., Ask, P., Persson, L., and Jansson, M. 2009. Light limitation of nutrient-poor lake ecosystems. Nature **460**: 506–509. doi:10.1038/nature08179.

Keeton, W.S., Copeland, E.M., Sullivan, S.M.P., and Watzin, M.C. 2017. Riparian forest structure and stream geomorphic condition: implications for flood resilience. Can. J. For. Res. **47**(4): 476–487. doi:10.1139/cjfr-2016-0327.

Kieta, K.A., Owens, P.N., Lobb, D.A., Vanrobaeys, J.A., and Flaten, D.N. 2018. Phosphorus dynamics in vegetated buffer strips in cold climates: a review. Environ. Rev. **26**(3): 255–272. doi:10.1139/er-2017-0077.

Kizuka, T., Akasaka, M., Kadoya, T., and Takamura, N. 2014. Visibility from roads predict the distribution of invasive fishes in agricultural ponds. PloS One **9**(6). doi:10.1371/journal.pone.0099709.

Kraus, J.M., Pomeranz, J.F., Todd, A.S., Walters, D.M., Schmidt, T.S., and Wanty, R.B. 2016. Aquatic pollution increases use of terrestrial prey subsidies by stream fish. J. Appl. Ecol. **53**(1): 44–53. doi:10.1111/1365-2664.12543.

Lee, P., Smyth, C., and Boutin, S. 2004. Quantitative review of riparian buffer width guidelines from Canada and the United States. J. Environ. Manage. **70**(2): 165–180. doi:10.1016/j.jenvman.2003.11.009.

Lehane, B., Giller, P., O'halloran, J., Smith, C., and Murphy, J. 2002. Experimental provision of large woody debris in streams as a trout management technique. Aquat. Conserv.-Mar. Freshw. Ecosyst. **12**(3): 289–311. doi:10.1002/aqc.516.

Lind, L., Hasselquist, E.M., and Laudon, H. 2019. Towards ecologically functional riparian zones: A meta-analysis to develop guidelines for protecting ecosystem functions and biodiversity in agricultural landscapes. J. Environ. Manage. **249**: 109391. doi:10.1016/j.jenvman.2019.109391.

Logez, M., Roy, R., Tissot, L., and Argillier, C. 2016. Effects of water-level fluctuations on the environmental characteristics and fish-environment relationships in the littoral zone of a reservoir. Fundam. Appl. Limnol. **189**(1): 37–49. doi:10.1127/fal/2016/0963.

Lyons, J., Trimble, S., and Paine, L. 2000. Grass versus trees: Managing riparian areas to benefit streams of central North America. J. Am. Water Assoc. **36**(4): 919–930. doi:10.1111/j.1752-1688.2000.tb04317.x.

MacConnachie, S., and Wade, J. 2016. Information in support of the identification of Critical Habitat for the Cowichan (Vancouver) Lamprey (*Entosphenus macrostomus*). DFO Can. Sci. Advis. Sec. Res. Doc., Fisheries and Oceans Canada.

Malcolm, I., Soulsby, C., Youngson, A., and Hannah, D. 2005. Catchment-scale controls on groundwater-surface water interactions in the hyporheic zone: Implications for salmon embryo survival. Riv. Res. Appl. **21**(9): 977–989. doi:10.1002/rra.861.

Martin, K.L.M., Van Winkle, R.C., Drais, J.E., and Lakisic, H. 2004. Beach-Spawning Fishes, Terrestrial Eggs, and Air Breathing. Physiol. Biochem. Zool. **77**(5): 750–759. doi:10.1086/421755.

Massicotte, P., Bertolo, A., Brodeur, P., Hudon, C., Mingelbier, M., and Magnan, P. 2015. Influence of the aquatic vegetation landscape on larval fish abundance. J. Great Lakes Res. **41**(3): 873–880. doi:10.1016/j.jglr.2015.05.010.

Master, L.L., Faber-Langendoen, D., Bittman, R., Hammerson, G.A., Heidel, B., Ramsay, L., Snow, K., Teucher, A., and Tomaino, A. 2012. NatureServe conservation status assessments: Factors for evaluating species and ecosystem risk. NatureServe, Arlington, VA. Available from http://www.natureserve.org/sites/default/files/publications/files/natureserveconservationstatusfactors_apr12_1.pdf.

Mickle, M.F., and Higgs, D.M. 2018. Integrating techniques: a review of the effects of anthropogenic noise on freshwater fish. Can. J. Fish. Aquat. Sci. **75**(9): 1534–1541. doi:10.1139/cjfas-2017-0245.

Miller, J.J., Curtis, T., Chanasyk, D.S., Reedyk, S., and Willms, W.D. 2016. Effectiveness of soil in vegetated buffers to retain nutrients and sediment transported by concentrated runoff through deep gullies. Can. J. Soil Sci. **96**(2): 154–168. doi:10.1139/cjss-2015-0038.

Modesto, V., Ilarri, M., Souza, A.T., Lopes-Lima, M., Douda, K., Clavero, M., and Sousa, R. 2018. Fish and mussels: Importance of fish for freshwater mussel conservation. Fish Fish. **19**(2): 244–259. doi:10.1111/faf.12252.

Mondal, S., and Patel, P.P. 2018. Examining the utility of river restoration approaches for flood mitigation and channel stability enhancement: a recent review. Environ. Earth Sci. **77**(5). doi:10.1007/s12665-018-7381-y.

Moore, A.P., and Bringolf, R.B. 2018. Effects of nitrate on freshwater mussel glochidia attachment and metamorphosis success to the juvenile stage. Environ. Pollut. **242**(A): 807–813. doi:10.1016/j.envpol.2018.07.047.

Moore, R., Spittlehouse, D., and Story, A. 2005. Riparian microclimate and stream temperature response to forest harvesting: A review. J. Am. Water Resour. Asoc. **41**(4): 813–834.

Murdoch, A., Mantyka-Pringle, C., and Sharma, S. 2020. The interactive effects of climate change and land use on boreal stream fish communities. Sci. Total Environ. **700**: 1–12. doi:10.1016/j.scitotenv.2019.134518.

Naiman and, R.J., and Décamps, H. 1997. The ecology of interfaces: Riparian Zones. Annu. Rev. Ecol. Syst. **28**(1): 621–658. doi:10.1146/annurev.ecolsys.28.1.621.

National Research Council. 2002. Riparian areas: Functions and strategies for management. National Academies Press, Washington, D.C. doi:10.17226/10327.

Nepf, H.M. 2012. Flow and transport in regions with aquatic vegetation. Annu. Rev. Fluid Mech. **44**(1): 123–142. doi:10.1146/annurev-fluid-120710-101048.

Nigel, R., Chokmani, K., Novoa, J., Rousseau, A.N., and Dufour, P. 2013. Recommendations for riparian buffer widths based on field surveys of erosion processes on steep cultivated slopes. Can. Water Resour. J. **38**(4): 263–279. doi:10.1080/07011784.2013.830815.

Nilsson, C., Jansson, R., Kuglerová, L., Lind, L., and Ström, L. 2013. Boreal riparian vegetation under climate change. ecosystems **16**(3): 401–410. doi:10.1007/s10021-012-9622-3.

Orozco-Lopez, E., Munoz-Carpena, R., Gao, B., and Fox, G.A. 2018. Riparian vadose zone preferential flow: Review of concepts, limitations, and perspectives. Vadose Zone J. **17**(1). doi:10.2136/vzj2018.02.0031.

Ouellet, V., Gibson, E.E., Daniels, M.D., and Watson, N.A. 2017. Riparian and geomorphic controls on thermal habitat dynamics of pools in a temperate headwater stream. Ecohydrology **10**(8). doi:10.1002/eco.1891.

Ow, L.F., and Ghosh, S. 2017. Urban cities and road traffic noise: Reduction through vegetation. Appl. Acoust. **120**: 15–20. doi:https://doi.org/10.1016/j.apacoust.2017.01.007.

Pearson, M. 2015. Recovery Potential Assessment for the Salish Sucker in Canada. Can. Sci. Advis. Sec. Res. Doc., DFO.

Pusey, B., and Arthington, A. 2003. Importance of the riparian zone to the conservation and management of freshwater fish: a review. Mar. Freshw. Res. **54**(1): 1–16. doi:10.1071/MF02041.

Raines, C.D., and Miranda, L.E. 2016. Role of riparian shade on the fish assemblage of a reservoir littoral. Environ. Biol. Fishes **99**(10): 753–760. doi:10.1007/s10641-016-0519-4.

Reid, A.J., Carlson, A.K., Creed, I.F., Eliason, E.J., Gell, P.A., Johnson, P.T.J., Kidd, K.A., MacCormack, T.J., Olden, J.D. ormerod, S.J., Smol, J.P., Taylor, W.W., Tockner, K., Vermaire, J.C., Dudgeon, D., and Cooke, S.J. 2019. Emerging threats and persistent conservation challenges for freshwater biodiversity. Biol. Rev. **94**(3): 849–873. doi:10.1111/brv.12480.

Richardson, J.S., and Sato, T. 2015. Resource subsidy flows across freshwater-terrestrial boundaries and influence on processes linking adjacent ecosystems. Ecohydrology **8**(3): 406–415. doi:10.1002/eco.1488.

Richardson, J.S., Taylor, E., Schluter, D., Pearson, M., and Hatfield, T. 2010. Do riparian zones qualify as critical habitat for endangered freshwater fishes? Can. J. Fish. Aquat. Sci. **67**(7): 1197–1204. doi:10.1139/F10-063.

Rood, S., Bigelow, S., Polzin, M., Gill, K., and Coburn, C. 2015. Biological bank protection: tress are more effective than grasses at resisting erosion from major river floods. Ecohydrology **8**(5): 772–779. doi:10.1002/eco.1544.

Rosgen, D.L. 1994. A classification of natural rivers. Catena **22**(3): 169–199. doi:10.1016/0341-8162(94)90001-9.

Rosgen, D.L. 2001. A practical method of computing streambank erosion rate. *In* Proceedings of the Seventh Federal Interagency Sedimentation Conference. Reno, Nevada. pp. 9–15. Available from https://semspub.epa.gov/work/01/554370.pdf.

Ruzzante, D.E., McCracken, G.R., Salisbury, S.J., Brewis, H.T., Keefe, D., Gaggiotti, O.E., and Perry, R. 2019. Landscape, colonization, and life history: their effects on genetic diversity in four sympatric species inhabiting a dendritic system. Can. J. Fish. Aquat. Sci. **76**(12): 2288–2302. doi:10.1139/cjfas-2018-0416.

Salafsky, N., Salzer, D., Stattersfield, A.J., Hilton-Taylor, C., Neugarten, R., Butchart, S.H.M., Collen, B., Cox, N., Master, L.L., O'Connor, S., and Wilkie, D. 2008. A Standard lexicon for biodiversity conservation: Unified Classifications of Threats and Actions: Classifications of Threats & Actions. Conserv. Biol. **22**(4): 897–911. doi:10.1111/j.1523-1739.2008.00937.x.

Scholz, A., Horrall, R., Cooper, J., and Hasler, A. 1976. Imprinting to chemical cues: The basis for home stream selection in salmon. Science **192**(4245): 1247–1249. doi:10.1126/science.1273590.

Seo, J.I., Nakamura, F., and Chun, K.W. 2010. Dynamics of large wood at the watershed scale: a perspective on current research limits and future directions. Landsc. Ecol. Eng. **6**(2): 271–287. doi:10.1007/s11355-010-0106-3.

Smiley, Jr., P.C., King, K.W., and Fausey, N.R. 2011. Influence of herbaceous riparian buffers on physical habitat, water chemistry, and stream communities within channelized agricultural headwater streams. Ecol. Eng. **37**(9): 1314–1323. doi:10.1016/j.ecoleng.2011.03.020.

Staton, S.K., Boyko, A.L., Dunn, S.E., and Burridge, M. 2012. Recovery Strategy for the Spotted Gar (*Lepisosteus oculatus*) in Canada. Fisheries and Oceans Canada, Ottawa.

Stutter, M., Kronvang, B., Huallachain, D.O., and Rozemeijer, J. 2019. Current insights into the effectiveness of riparian management, attainment of multiple benefits, and potential technical enhancements. J. Environ. Qual. **48**(2): 236–247. doi:10.2134/jeq2019.01.0020.

Sweeney, B.W., and Newbold, J.D. 2014. Streamside forest buffer width needed to protect stream water quality, habitat, and organisms: a literature review. J. Am. Water Resour. Assoc. **50**(3): 560–584. doi:10.1111/jawr.12203.

Trancart, T., Feunteun, E., Danet, V., Carpentier, A., Mazel, V., Charrier, F., Druet, M., and Acou, A. 2018. Migration behaviour and escapement of European silver eels from a large lake and wetland system subject to water level management (Grand-Lieu Lake, France): New insights from regulated acoustic telemetry data. Ecol. Freshw. Fish **27**(2): 570–579. doi:10.1111/eff.12371.

Vargas-Luna, A., Crosato, A., Anders, N., Hoitink, A.J.F., Keesstra, S.D., and Uijttewaal, W.S.J. 2018. Morphodynamic effects of riparian vegetation growth after stream restoration: Morphodynamic effects of riparian vegetation growth after restoration. Earth Surf. Process. Landf. **43**(8): 1591–1607. doi:10.1002/esp.4338.

Warren, D.R., Kraft, C.E., Keeton, W.S., Nunery, J.S., and Likens, G.E. 2009. Dynamics of wood recruitment in streams of the northeastern US. For. Ecol. Manag. **258**(5): 804–813. doi:10.1016/j.foreco.2009.05.020.

Wohl, E. 2015. Legacy effects on sediments in river corridors. Earth-Sci. Rev. **147**: 30–53. doi:10.1016/j.earscirev.2015.05.001.

Wood, P., and Armitage, P. 1997. Biological effects of fine sediment in the lotic environment. Environ. Manage. **21**(2): 203–217. doi:10.1007/s002679900019.

Yu, C., Duan, P., Yu, Z., and Gao, B. 2019. Experimental and model investigations of vegetative filter strips for contaminant removal: A review. Ecol. Eng. **126**: 25–36. doi:10.1016/j.ecoleng.2018.10.020.

Zawal, A., Lewin, I., Stepien, E., Szlauer-Lukaszewska, A., Buczynska, E., Buczynski, P., and Stryjecki, R. 2016. The influence of the landscape structure within buffer zones, catchment land use and instream environmental variables on mollusc communities in a medium-sized lowland river. Ecol. Res. **31**(6): 853–867. doi:10.1007/s11284-016-1395-2.

GLOSSARY

Acoustic environment: Relating to sound in an environment.

Anthropogenic: Anything originating from human activity.

(Aquatic species) Habitat: Spawning grounds and nursery, rearing, food supply, migration and any other areas on which aquatic species depend directly or indirectly to carry out their life processes or areas where aquatic species formerly occurred and have the potential to be reintroduced.

Areas of upwelling: Areas where deep, cold water rises toward the surface; these areas are often rich in nutrients.

Attribute: Attributes are measurable properties or characteristics of a feature. Attributes describe how a given feature supports the identified functions necessary for the species' life processes. Together, the attributes allow the feature to support the function. In essence, attributes provide the greatest level of information about a feature.

Attachment: The physical connection by which a mussel is attached.

Avoidance: Finding protection or cover from predators or adverse environmental conditions.

Backwater: A still water section of a stream or river beside the main flow but separated by a ridge or land or habitat at the margin of a riffle or run; often separated from the source during dry seasons.

Bank: The land directly on the edge of a waterbody.

Beach: A pebbly or sandy shore between high- and low-water marks.

Beach rubbing: The act of rubbing part(s) of the body on a substrate.

Birthing: The act of giving birth to young.

Communication: The sharing of information; a means of connection.

Contaminants: Substances that are considered to be toxic to organisms or having an effect on water quality.

Courtship: The behaviour of animals aimed at attracting a mate.

Cover: Something that supports species needs such as resting, predator avoidance, and protects against adverse environmental conditions.

Critical Habitat: Habitat that is necessary for the survival or recovery of a listed wildlife species and that is identified as the species' critical habitat in the Recovery Strategy or in an Action Plan for the species.

Dispersal: The movement of individuals away from their natal site to other habitats and other individuals.

Dissolved oxygen: The level of free oxygen dissolved in water that is available to living organisms.

Eddies: The swirling of water and the reverse current created when the water flows past an obstacle.

Erosion: Erosion is the process of soil gradually wearing away by wind, water or gravity.

Feature: Features are the essential structural components that provide the requisite function(s) to meet the species' needs. Features may change over time and usually comprise more than one attribute. A change or disruption to the feature or any of its attributes may affect the function and its ability to meet the biological needs of the species.

Feeding: Eating food or prey.

Filtration: Filtration is the process of removing matter, light or sound from air or water.

Floodplain: An area of low-lying ground directly surrounding a river, often subject to flooding.

Food supply: The quality/quantity/accessibility of food.

Foraging: Searching for food or prey.

Forest: An area of land covered mainly by trees.

Function: A life-cycle process of the listed species taking place in Critical Habitat. The identification of Critical Habitat must describe how the functions support a life process necessary for the survival or recovery of species at risk.

Glides: Slow-moving, non-turbulent flow; a glide is too shallow to be a pool and the current is too slow to be a run.

Groundwater recharge area: An area of land where precipitation and surface water is able to infiltrate the ground and enter the water table.

Growth: The process that a living organism goes through as it transitions through various life stages to adulthood.

Host species: The presence of a species able to host smaller organisms while they complete a life-cycle process necessary for survival or recovery.

Incubation: A phase in which eggs or embryos are kept clean and/or the biophysical and chemical properties of the eggs or embryos are maintained.

Infiltration: Infiltration is the process by which surface water enters the soil.

Upstream habitat: The habitat within a stream that is upstream of a critical habitat feature.

Isolation: Isolation is the process of causing a place or thing to be distanced from a disturbance.

Lake benthic habitat: Lake bottom.

Lake littoral habitat: Shallow, nearshore area often with rooted vegetation.

Lake pelagic habitat: Open water beyond littoral area; water column.

Larval settling: A phase in which swimming larvae transform and adopt a benthic lifestyle.

Meandering: Meandering is the process of a stream or river moving back and forth, changing shape as it flows across a floodplain or valley eroding and depositing sediments on alternating banks.

Meander belt: The space that a meandering watercourse occupies on its floodplain.

Migration: The periodic or seasonal movement of large numbers of individuals from one area or population to another.

Migration/movement corridors: Contiguous areas of natural habitat through which animals are able to migrate and move.

Molting: The shedding of an outer layer of epidermis.

Nest building: The act of creating a nest.

Nest defense: The act of defending a nest against predators, heterospecifics or conspecifics.

Nutrients (P, N, C, Ca): Organic and inorganic substances in the water than can be used by an organism to survive, grow and reproduce.

Overwintering: Spending winter in or at a particular place.

Photic environment: The uppermost layer of a waterbody that receives sunlight. Depth of photic environment can change dependent on turbidity of water.

Physical space: Space surrounding an individual.

Pools: Deeper areas of still water.

Rearing: Supporting offspring development to maturity or self-sufficiency, usually through nurturing care.

Reproduction: The process by which organisms give rise to offspring, and which fundamentally consists of the segregation of a portion of the parental body by a sexual or asexual process and its subsequent growth and differentiation into a new individual, which includes but is not limited to mating, spawning, gestation, birthing, calving, whelping, and dispersion.

Reproductive isolation: Habitat barriers that prevent members of different species from producing offspring, maintaining the integrity of the species by reducing gene flow between related species.

Residence: a dwelling-place, such as a den, nest or other similar area or place, that is occupied or habitually occupied by one or more individuals during all or part of their life cycles, including breeding, rearing, staging, wintering, feeding or hibernating.

Resting: A bodily state characterized by reduced functional and metabolic activities.

Riffles: Fast flowing, well-aerated and shallow areas.

Riparian habitat: The blend of streambed, water, trees, shrubs, and grasses in an area, which provides or directly influences aquatic habitat.

Riparian Zone: The area located between a waterbody's edge and the upland area.

Runs: Moderate current and smooth surface water.

Salinity: The level of dissolved inorganic salt in a waterbody.

Shading: Shading is the process of adjusting the amount of light admitted onto a surface.

Slope: The degree of incline of land surrounding a waterbody. Affects how surface water and precipitation enter a waterbody, with steeper slopes contributing surface waters much faster and possibly leading to increased contamination and nutrient loading.

Socializing: Refers to the developmental processes through which individuals learn necessary behaviours such as but not limited to foraging, migration, and altruistic behaviours.

Staging: Congregation of individuals in preparation for reproduction or migration.

Subsidization: Subsidization is the process of transferring energy, food, and structural components from the terrestrial habitat to the aquatic habitat.

Shoals: Relatively shallow areas that may or may not be near the waterbody margin; these areas may become unsubmerged during periods of low rainfall.

Sympatric species: The presence in sufficient abundance of species that co-exist in sympatry with another and is required for the maintenance of the ecological and evolutionary processes driving reproductive isolation and sympatric species pairs.

Wetlands: Land submerged or permeated by water, either permanently or temporarily, and are characterized by vegetation adapted to saturated soil conditions. Areas included, but not limited to are: fresh and salt water marshes, swamps, bogs, fens, seasonally flooded forest, and sloughs.

Wood recruitment: Wood recruitment is the addition of wood into waterbodies from the associated riparian forest as a result of the mortality of individual trees, disturbances affecting multiple trees or meandering of a river or stream channel.

APPENDIX 1: LITERATURE REVIEW

The review followed the key components and principals of a systematic review (Collaboration for Environmental Evidence 2018) with reduced documentation steps to limit the amount of time required to complete the review. The steps were as follows: 1) develop a list of search terms and Boolean operators, 2) search literature databases using the search terms, 3) identify inclusion criteria to determine if studies were included for further evaluation, and 4) extract data.

The final list of search terms were placed in four categories: 1) aquatic critical habitat feature; species of interest; 2) different types or terms for freshwater habitats; 3) different terms for riparian habitat; and 4) terms linking riparian and freshwater (Table A1.1).

Articles include peer-reviewed journals and grey literature. Our main search focused on Web of Science as this is a primary science-based database of peer-reviewed literature. We used DFO library to obtain access to any literature that may not be available in an online format. Only the English language was used during the search and only English language results were included. We also included papers that were identified during targeted searches or exploration based on references or papers sent to us from colleagues.

Each paper was first screened at the title and abstract level for relevance (Figure A1.1). Papers that met the inclusion criteria were then assessed at the full text level. Briefly, papers were included if they identified riparian habitat and their link to functions, aquatic features or water quality attributes relevant to fishes or mussels. Results of recent papers (i.e., last 5-10 years) were given precedence over older papers that may provide outdated information.

Table A1.1: Terms and Boolean operators used to search Web of Science and ProQuest literature databases.

Aquatic feature or water quality attribute or function	**Aquatic features, functions, and water quality attributes from a standardized list and related terms (Table 2)**
	AND
Subject	(Fish* OR Mussel* OR Mollusc*)
	AND
Freshwater	("Fresh water" OR Freshwater* OR Stream* OR River* OR Wetland* OR Marsh* OR Swamp* OR Lake*)
	AND
Riparian	(Riparian* OR Terrestrial* OR Shoreline* OR Land* OR Buffer* OR Forest* OR Anthro*)
	AND
Link	(Impact* OR Affect* OR Effect* OR Subsid* OR Link*)

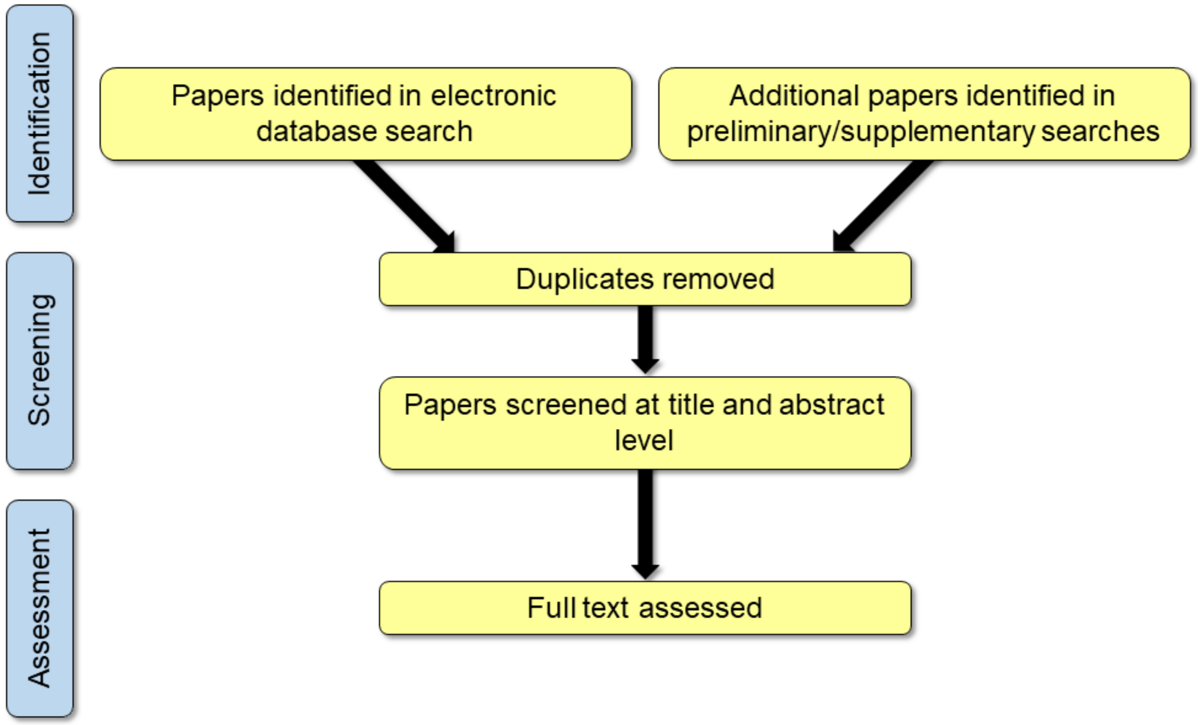

Figure A1.1: Literature review work flow.

OVERVIEW OF LITERATURE REVIEW RESULTS

Of the over thirteen thousand papers gathered for this analysis, 762 unique articles, books, and reports were screened at the abstract/title level and 185 full texts were assessed (Table A1.2). Of the 762 unique articles screened at abstract/title level, the oldest article is from 1976, and there is a steadily increasing number of articles over time (Figure A1.2a). The five most popular journals were: Freshwater Biology (42 articles), Canadian Journal of Fisheries and Aquatic Science (29 articles), Hydrobiologia (27 articles), River Research and Applications (25 articles), and Science of the Total Environment (24 articles). Word clouds created from the top 100 words in the titles show that most papers are related to rivers or streams rather than lakes and wetlands, and that research on fish was more prevalent in the database than on mussels (Figure A1.2b).

A1 REFERENCES

Collaboration for Environmental Evidence. 2018. Guidelines and standards for evidence synthesis in environmental management. Version 5.0. Available from www.environmentalevidence.org/information-for-authors.

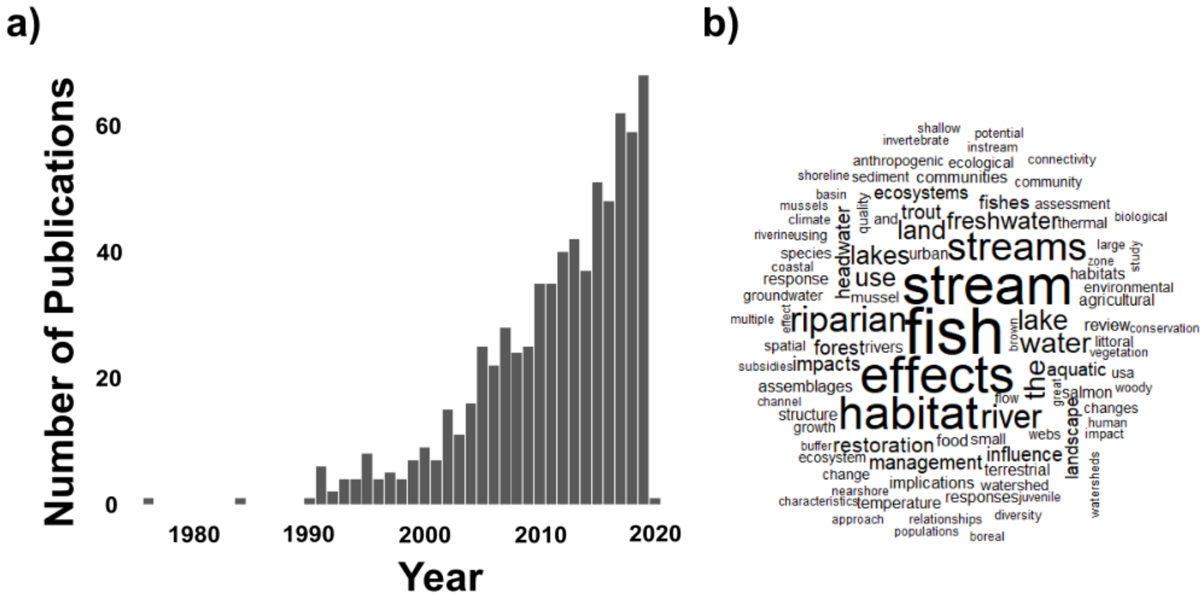

Figure A1.2: Information about articles, reports, and books found in literature review. (a) Number of publications per year and (b) word cloud created from the top 100 words in the examined titles.

Table A1.2: Terms used in the literature reserach and number of results.

Aquatic features, water quality attributes, and functions	Terms	After duplicates removed	Screened at title/abstract	Full text assessed
Features				
acoustic environment	(acoustic* OR soundscape* OR noise*)	143	14	10
areas of upwelling	(upwelling* OR groundwater* OR "ground water")	325	37	10
backwater	(backwater* OR "back water")	48	17	8
cover	(cover* OR refug* OR shelter*)	1617	119	9
eddies	(eddies OR eddy)	20	4	4
food supply	("food supply" OR "food availability" OR "prey availability" OR subsid*)	574	48	10
glides	glide*	9	7	4
host species	Subject REDUCED to just (mollusc and mussel*); (host*)	81	12	4
upstream habitat	(inlet* OR outlet* OR "upstream habitat" OR headwater*)	687	78	10
lake benthic habitat	Freshwater REDUCED to just Lake*; (bottom OR benthic)	465	28	5
lake littoral habitat	Freshwater REDUCED to just Lake*; (littoral* OR "near shore" OR nearshore)	416	41	6
lake pelagic habitat	Freshwater REDUCED to just Lake*; (pelagic* OR "open water" OR "water column")	288	20	2
migration/movement corridors	("migration corridor*" OR connectivit* OR "movement corridor*" OR "barrier free" OR "contiguous habitat*")	656	36	11
photic environment	(photic* OR light* OR clarity)	448	41	4

Aquatic features, water quality attributes, and functions	Terms	After duplicates removed	Screened at title/abstract	Full text assessed
physical space	("physical space" OR "activity space")	4	0	0
pools	(pool* OR "still water")	484	70	6
riffles	(riffle* OR aerat*)	168	58	7
runs	run*	372	28	3
shoals	(shoal* OR sandbar* OR sandbank* OR "sand bank" OR "sand bar" OR "gravel bar" OR "gravelbar")	68	10	5
sympatric species	("sympatric species" OR "sympatric pairs")	8	1	1
Water Quality Attributes				
dissolved oxygen	(oxygen OR hypoxia OR anox*)	666	27	5
temperature	"water temperature*"	424	71	8
contaminants	(contaminant* OR metal* OR chemical* OR pesticide* OR herbicide*)	1827	85	13
salinity	(salinity OR salt*)	872	13	4
nutrients (P,N,C, Calcium)	(Phosph* OR Nitr* OR Carbon* OR calcium)	1810	100	12
pH	pH	465	58	10
Functions				
attachment	attachment	2	0	0
avoidance	(avoidance OR Burying OR Camouflaging OR Hiding OR "taking cover" OR "taking refuge")	40	0	0
beach rubbing	"beach rubbing"	0	0	0
birthing	birthing	1	0	0
communication	(communication OR calling OR vocalization OR socializing)	24	0	0
courtship	courtship	0	0	0

Aquatic features, water quality attributes, and functions	Terms	After duplicates removed	Screened at title/abstract	Full text assessed
dispersal	(dispersal OR drifting OR "passive movement")	99	1	1
feeding	feed*	124	2	2
foraging	forag*	37	0	0
growth	(growth OR ageing OR development OR maturation)	379	0	0
incubation	incubation	5	1	1
larval settling	"larval settling"	0	0	0
migration	migration	75	1	1
molting	molting	0	0	0
nest building	("nest building" OR "den creation" OR "nest creation" OR "redd creation")	1	0	0
nest defense	"nest defense"	0	0	0
overwintering	(overwintering OR "over wintering")	4	0	0
rearing	(rearing OR nursing OR nurturing OR suckling)	36	6	5
reproduction	(repro* OR breeding OR "egg deposition" OR "mating" OR "fertilization" OR "spawning")	237	4	4
reproductive isolation	("reproductive isolation" OR "natural mate selection' OR "maintenance of sympatry")	3	0	0
resting	(rest* OR diapausis OR hibernation OR dormancy)	21	0	0
socializing	social*	26	0	0
staging	staging	104	0	0

APPENDIX 2: CANADIAN JURISDICTIONAL REGULATION AND RECOMMENDATIONS

Many provinces and territories have their own regulations and recommendations regarding the extent of habitat surrounding waterbodies that should be protected depending on the source of disturbance (i.e., agriculture, forestry or development) (Table A2.1).

Table A2.1: Riparian buffer widths for water features and aquatic species protection as found in government regulations and recommendations across Canadian Provinces and Territories.

Jurisdiction	Incentive	Width of buffer (m)	Habitat requiring buffer	Comments	Source
Agriculture					
Alberta	Regulation	1–30	open waterbody	herbicide application, width dependent on application style and herbicide type	Government of Alberta 2010
Alberta	Regulation	0	open body of water	insecticides for pest control purposes up to and including the bed and shore of an open body of water provided the insecticide does not enter into or onto the body of water	Government of Alberta 2010
Alberta	Regulation	0	open body of water	rodenticides for pest control purposes up to and including the bed and shore of an open body of water provided the insecticide does not enter into or onto the body of water	Government of Alberta 2010
British Columbia	Regulation	30	water supply intake	pesticide application around a water supply for livestock or irrigation	Government of British Columbia 2016
New Brunswick	Regulation	30–75	intake of a public water supply system	agricultural activities	Government of New Brunswick 2001

Jurisdiction	Incentive	Width of buffer (m)	Habitat requiring buffer	Comments	Source
New Brunswick	Regulation	15–75	intake of a public water supply system	pesticide application	Government of New Brunswick 2001
New Brunswick	Regulation	15–75	intake of a public water supply system	livestock grazing	Government of New Brunswick 2001
New Brunswick	Regulation	5	intake of a public water supply system	hay removal	Government of New Brunswick 2001
New Brunswick	Regulation	30–75	any watercourse	installation and operation of gasoline or diesel powered pumps	Government of New Brunswick 2001
New Brunswick	Regulation	30–75	within 1 km of the intake of a public water supply system	pesticide application	Government of New Brunswick 2001
Newfoundland Labrador	Regulation	30	neighbouring well	pesticide application	Government of Newfoundland and Labrador 2013
Newfoundland Labrador	Best Practices	15–400	all waterbodies	dependent on land use. increases with slope greater than 30% of the width of the buffer zone	Agriculture and Agri-Food Canada
Ontario	Recommendation	30	all waterbodies	agriculture activities	ECCC 2013
Prince Edward Island	Regulation	15–30	all waterbodies	buffer zones 15 m wide must be maintained next to all watercourses and wetlands. the regulations also require the planting of 10 m wide grassed headlands at the end of all row of cropland that ends within 200 m of a watercourse or wetland	Agriculture and Agri-Food Canada; Government of Prince Edward Island 2016

Jurisdiction	Incentive	Width of buffer (m)	Habitat requiring buffer	Comments	Source
Québec	Regulation	1–100	open body of water	pesticide application without aircraft, dependent on slope	Gouvernement du Québec 2018
Québec	Regulation	30-100	open body of water	Pesticide application with aircraft	Gouvernement du Québec 2018
Québec	Regulation	3	open body of water	cultivation of soil for agriculture purposes	Gouvernement du Québec 2019
Saskatchewan	Recommendation	10–30	all waterbodies	guide for landowners on improving riparian zones on their property	Huel 1998
Yukon	Regulation	30	open body of water	pesticide application, unless permit allows	Government of Yukon 1994
Forestry					
Alberta	Regulation	0	open body of water	insecticides for pest control purposes up to and including the bed and shore of an open body of water provided the insecticide does not enter into or onto the body of water	Government of Alberta 2010
Alberta	Regulation	1–30	open waterbody	herbicide application, width dependent on application type	Government of Alberta 2010
Alberta	Ground Rules	30	small permanent streams	ground rules apply to timber harvest	Alberta Sustainable Resource Development 2005
Alberta	Ground Rules	60	large permanent streams	ground rules apply to timber harvest	Alberta Sustainable Resource Developmen, 2005

Jurisdiction	Incentive	Width of buffer (m)	Habitat requiring buffer	Comments	Source
British Columbia	Regulation	0–50	streams	width depends on classification of stream and if fish bearing	Tschaplinski and Pike 2010
British Columbia	Regulation	0–10	lakes, wetlands	width depends on classification of waterbody	Tschaplinski and Pike 2010
British Columbia	Regulation	1–10	waterbody, dry stream or wetland	pesticide application around a waterbody, 10 m unless permitted for certain applications.	Government of British Columbia 2016
New Brunswick	Regulation	15–75	intake of a public water supply system	tree planting	Government of New Brunswick 2001
New Brunswick	Regulation	15–75	intake of a public water supply system	selection cutting	Government of New Brunswick 2001
New Brunswick	Regulation	30–75	any watercourse	installation and operation of gasoline or diesel powered pumps	Government of New Brunswick 2001
Newfoundland Labrador	Best Practices	15–400	all waterbodies	dependent on land use. increases with slope greater than 30% of the width of the buffer zone	Agriculture and Agri-Food Canada
Nova Scotia	Regulation	20–60	all waterbodies	forest sustainability regulations	Agriculture and Agri-Food Canada
Ontario	Recommendation	30	all waterbodies	forestry activities	ECCC 2013
Prince Edward Island	Regulation	20–30	all waterbodies	buffer zones 15 metres wide must be maintained next to all watercourses and wetlands.	Agriculture and Agri-Food Canada; Government of Prince Edward Island 2016

Jurisdiction	Incentive	Width of buffer (m)	Habitat requiring buffer	Comments	Source
Québec	Regulation	1–100	open body of water	pesticide application without aircraft, dependent on slope	Gouvernement du Québec 2018
Québec	Regulation	30-100	open body of water	Pesticide application with aircraft	Gouvernement du Québec 2018
Québec	Regulation	20	lakes and rivers	forestry activities, from the edge of the riparian ecotone (10-15 m)	Gouvernement du Québec 2017; Gouvernement du Québec 2019
Saskatchewan	Recommendation	10–30	all waterbodies	guide for landowners on improving riparian zones on their property	Huel 1998
Yukon	Regulation	30	open body of water	pesticide application, unless permit allows	Government of Yukon 1994
Yukon	Regulation	5–80	streams and rivers	dependent on stream class	Yukon Energy, Mines and Resources Forestry Management Branch 2011a
Yukon	Regulation	20–60	lakes	dependent on lake class	Yukon Energy, Mines and Resources Forestry Management Branch 2011a
Yukon	Regulation	5–60	wetlands	dependent on wetland class	Yukon Energy, Mines and Resources Forestry Management Branch 2011b
Development					
Alberta	Regulation	1–30	open body of water	herbicide application, width dependent on application type	Government of Alberta 2010
Alberta	Regulation	250	surface water intake	mosquito control pesticide application	Government of Alberta 2010

Jurisdiction	Incentive	Width of buffer (m)	Habitat requiring buffer	Comments	Source
Alberta	Regulation	0	open body of water	insecticides for pest control purposes up to and including the bed and shore of an open body of water provided the insecticide does not enter into or onto the body of water	Government of Alberta 2010
Alberta	Regulation	0	open body of water	rodenticides for pest control purposes up to and including the bed and shore of an open body of water provided the insecticide does not enter into or onto the body of water	Government of Alberta 2010
British Columbia	Regulation	30	water intake or well	pesticide application around a water intake or well	Government of British Columbia 2016
British Columbia	Regulation	1–10	waterbody, dry stream or wetland	pesticide application around a waterbody, 10 m unless permitted for certain applications.	Government of British Columbia 2016
British Columbia	Regulation	30	all waterbodies	development activities in the municipalities and regional districts in the lower mainland, much of vancouver island, and areas f the southern interior of the province	Government of British Columbia 2019
Manitoba	Regulation	3–35	all waterbodies	application of substances containing nitrogen or phosphorus	Government of Manitoba 2008
Manitoba	Regulation	15–30	all waterbodies	development, dependent on land use and waterbody type	Government of Manitoba 2011

Jurisdiction	Incentive	Width of buffer (m)	Habitat requiring buffer	Comments	Source
New Brunswick	Regulation	5	all watercourses	landscaping	Government of New Brunswick 2001
New Brunswick	Regulation	15	all watercourses	tree removal	Government of New Brunswick 2001
New Brunswick	Regulation	30–75	all watercourse	installation and operation of gasoline or diesel powered pumps	Government of New Brunswick 2001
Newfoundland Labrador	Best Practices	15–400	all waterbodies	dependent on land use. increases with slope greater than 30% of the width of the buffer zone	Agriculture and Agri-Food Canada
Nova Scotia	Regulation	0–1	all waterbodies	any activity near or in a watercourse	Province of Nova Scotia 2015
Ontario	Recommendation	120	all waterbodies	significant habitat of endangered and threatened species	Government of Ontario 2010
Ontario	Recommendation	120	wetlands	significant wetlands and significant coastal wetlands	Government of Ontario 2010
Ontario	Recommendation	120–300	fish habitat	inland lake trout lake (at capacity) on the Canadian shield 300 m all other fish habitat 120 m	Government of Ontario 2010
Québec	Regulation	3–100	open body of water	pesticide application	Gouvernement du Québec 2018
Québec	Regulation	15–20	open body of water	structures, undertakings and works for municipal, commercial, industrial, public or public access purposes	Gouvernement du Québec 2019

Jurisdiction	Incentive	Width of buffer (m)	Habitat requiring buffer	Comments	Source
City of Mont-Laurier, Québec	Regulation	3–15	Lac des Écorces	dependent on property type, for entire border of Lac des Écorces for protection of Spring Cisco	DFO 2014
Saskatchewan	Recommendation	10–30	all waterbodies	guide for landowners on improving riparian zones on their property	Huel 1998
Yukon	Regulation	30	open body of water	pesticide application, unless permit allows	Government of Yukon 1994
Whitehorse, Yukon	Regulation	50	all waterbodies	minimum riparian setback zone within municipal limits. does not apply to private lands	UMA Engineering Ltd., Environmental Dynamics Inc. 2004

A2 REFERENCES

Agriculture and Agri-Food Canada. *Beneficial management practices for riparian zones in Atlantic Canada*. http://www.nsfa-fane.ca/efp/wp-content/uploads/2019/09/BMP-Atlantic-riparian_zones.pdf

Alberta Sustainable Resource Development. 2005. *Review of Riparian Management Policy in Alberta's Forests*. Riparian Management Committee Alberta Sustainable Resource Development.

DFO. 2014. *Recovery Strategy for the Spring Cisco (Coregonus sp.), Recovery Strategy Series of the Species at Risk Act*, Fisheries and Oceans Canada, Ottawa, vi + 24 p.

Environment Canada. 2013. *How Much Habitat is Enough?* Third Edition. Environment Canada, Toronto, Ontario.

Gouvernement du Québec. 2017. *Regulation on the sustainable management of forests in the domain of the State:Sustainable Forest Development Act*. Gouvernement du Québec, Québec City, Québec.

Gouvernement du Québec. 2018. *Règlement modifiant le Code de gestion des pesticides : règlement modifiant le Règlement sur les permis et les certificats pour la vente et l'utilisation des pesticides*. Gouvernement du Québec, Québec City, Québec.

Gouvernement du Québec. 2019. *Protection Policy for Lakeshores, Riverbanks, Littoral Zones and Floodplains, Environment Quality Act*. Gouvernement du Québec, Québec City, Québec.

Government of Alberta, 2010. *Environmental code of practice for pesticides, RSA 2000*. Alberta Queen's Printer, Edmonton, Alberta.

Government of British Colombia. 2016*. Integrated pesticide management regulation, 235*. Queen's Printer, Victoria, British Colombia.

Government of British Columbia. 2019. *Riparian Areas Protection Regulation, BC Reg 178/2019.* <http://canlii.ca/t/53pnx> retrieved on 2020-02-03. Government of British Columbia, Victoria, British Colombia

Government of Manitoba, 2008. *Nutrient Management Regulation under The Water Protection Act*. Government of Manitoba, Winnipeg, Manitoba.

Government of Manitoba. 2011. *The Planning Act: Provincial Planning Regulation*. Government of Manitoba, Winnipeg, Manitoba.

Government of New Brunswick. 2001. *Watershed Protected Area Designation Order - Clean Water Act*. Government of New Brunswick , Fredericton, New Brunswick.

Government of Newfoundland and Labrador, 2013. *Agriculture pesticide applicator license terms and conditions*, in: Department of Environment and Conservation (Ed.). Government of Newfoundland and Labrador, St. John's, Newfoundland and Labrador.

Government of Yukon. 1994. *Environment Act*, 125. Government of Yukon, Whitehorse, Yukon.

Huel, D., 1998. *Streambank Stewardship: A Saskatchewan Riparian Project*. Saskatchewan Wetland Conservation Corporation. Regina, Sk.

Ontario Ministry of Natural Resources. 2010. *Natural Heritage Reference Manual for Natural Heritage Policies of the Provincial Policy Statement, 2005*. Second Edition. Toronto: Queen's Printer for Ontario. 248 pp.

Prince Edward Island Department of Communities, Land and Environment. 2016. *Prince Edward Island Watercourse, Wetland and Buffer Zone Activity Guidelines.* Government of Prince Edward Island, Charlottetown, Prince Edward Island. <https://www.princeedwardisland.ca/sites/default/files/publications/watercourse_wetland_and_buffer_zone_activity_guidelines_dec_2016.pdf> retrieved on 2020-03-17.

Province of Nova Scotia. 2015. *Guide to Altering Watercourses*. Province of Nova Scotia, Halifax, Nova Scotia. <https://novascotia.ca/nse/watercourse-alteration/docs/NSE-Watercourse-Alteration-Program-May29.pdf> retrieved on 2020-03-17.

Tschaplinski, P. J., & Pike, R. G. (2010). Riparian management and effects on function. In Compendium of forest hydrology and geomorphology in British Columbia. RG Pike, TE Redding, RD Moore, RD Winker, and KD Bladon (editors). BC Ministry of Forests and Range, Forest Science Program. Victoria, BC, and FORREX Forum for Research and Extension in Natural Resources, Kamloops, BC. Land Management Handbook (Vol. 66, pp. 479-526).

UMA Engineering Ltd., Environmental Dynamics Inc. 2004. *City of Whitehorse Watershed Management Plan Vol. 2: Risk assessment and risk management strategies for drinking water protection*. Whitehorse, Yukon.

Yukon Energy, Mines and Resources Forestry Management Branch. 2011a. *Forest resources regulation: Riparian Management on Streams and Lakes Standards and Guidelines*. Whitehorse, Yukon.

Yukon Energy, Mines and Resources Forestry Management Branch. 2011b. *Forest resources regulation: Wetlands Riparian Standards and Guidelines*. Whitehorse, Yukon.