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Science on the use of timing windows as a mitigation measure

Tyler D. Tunney[1], Douglas C. Braun[2,3], Jonathan D. Midwood[4], Sean M. Naman[2],
and Jordan Roszell[1]

[1] Gulf Fisheries Centre
Fisheries and Oceans Canada
343 Universite Ave
Moncton, NB E1C 5K4

[2]Freshwater Ecosystems
Science Branch, Pacific Region
Fisheries and Oceans Canada
4222 Cultus Valley Road
Cultus Lake BC, V2R 5B6

[3]School of Resource and Environmental Management
Simon Fraser University
8888 University Drive
Burnaby BC, V5A 1S6

[4]Great Lakes Laboratory for Fisheries and Aquatic Sciences
Science Branch, Ontario and Prairie Region
Fisheries and Oceans Canada
867 Lakeshore Rd
Burlington, ON L7S 1A1

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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

Timing windows refer to a mitigation measure that defines low-risk periods for harm to fish and fish habitat from works, undertaking and activities (WUAs). The Fisheries and Oceans Canada Fish and Fish Habitat Protection Program (FFHPP) has requested scientific advice on the use of timing windows. To address this request, this document is structured around three main objectives outlined in the terms of reference. First, a literature search was conducted, and found that there is a paucity of peer reviewed scientific research connected to timing windows, and that literature on timing windows is dominated by material on dredging activities. An in-depth treatment of rationale, effectiveness, and frameworks for timing windows is provided. Canadian timing window use, rationale, and considerations varies among provinces and territories, but spawning is often cited as the fish life process targeted for protection. Second, a conceptual model outlines a set of rationale and considerations for the creation or modification of timing windows focusing on (1) the timing and vulnerability of fish life processes, (2) the characteristics of WUAs and associated pressures, and (3) the characteristics of habitat and environmental conditions. Importantly, life processes vary in their vulnerability to WUAs, but characteristics such as well-defined and predictable timing were identified among the factors that make some more suitable to mitigation with timing windows than others. Further considerations for migration, spawning, feeding, natal, rearing and refuge use are also presented. Characteristics of WUA pressures, including timing and persistence, were also identified as key factors for timing windows to consider. The interaction of pressures with fish habitat will be influenced by characteristics of the habitat and the environmental context. Protecting habitat processes with timing windows will depend on the process predictability, the mechanisms that regulate the WUA pressure and the habitat process, and the degree of overlap and strength of the pressure during exposure. Finally, we present a three-tiered approach to evaluate the effectiveness of timing windows to reduce the risk of exposure of fish life or habitat processes, the effects of pressures on the exposed process, and risk at the population level. Studies at each tier can inform comparisons of how risk varies through time, which is a key consideration when choosing among timing window options. This document advances the state of knowledge on the use of timing windows and on evaluating their effectiveness. The information presented can be used by FFHPP in the development of a science-based timing window framework to guide their creation and modification, to aid practitioners to identify potential risks of WUAs outside of established windows, and to inform their adaptation to changing environmental conditions.

1. INTRODUCTION

The Fish and Fish Habitat Protection Program (FFHPP) at Fisheries and Oceans Canada has a regulatory regime in place to avoid, mitigate, and offset the undesirable consequences of works, undertakings, and activities (WUAs) other than fishing on fish and fish habitat (DFO 2019a). As part of the risk management process (See Section 3 below), a Pathways of Effects (PoE) approach is used to identify the linkages from WUAs and their pressures to endpoints that are harmful to fish and fish habitat - i.e., (1) death of fish (*Fisheries Act* section 34.4) and (2) impairment of fish habitat to support the life processes of fish (*Fisheries Act* section 35) (Brownscombe and Smokorowski 2021). When WUAs have undesirable endpoints that cannot be avoided completely, mitigations are applied to reduce the spatial scale, duration, and intensity of pressures (DFO 2019a) (Figure 1).

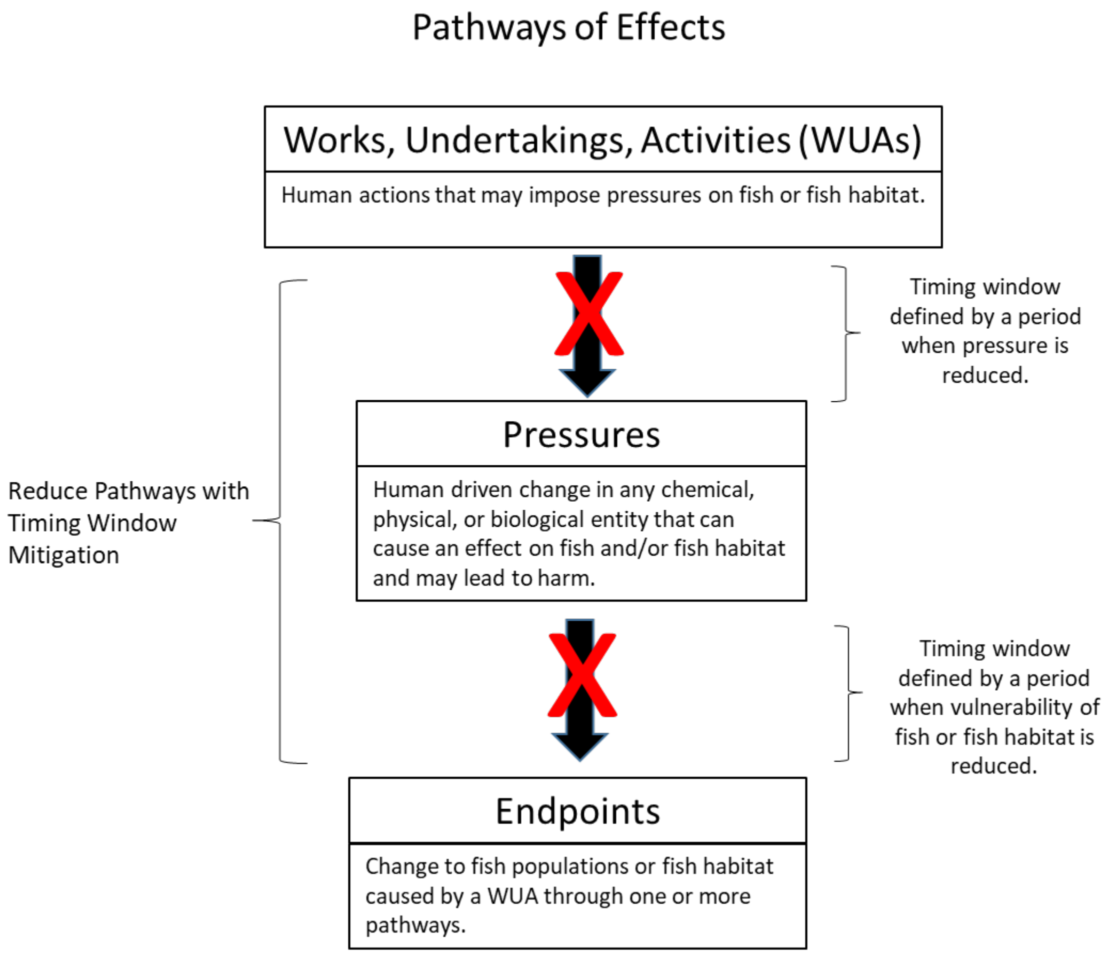

Figure 1. Schematic of how timing windows can be used as a mitigation measure to break the links between key components along pathways of effects. Timing Windows can be used to reduce the pressure exerted by a WUA (e.g., work is conducted at a time of year when pressure can be reduced). A timing window could also be used to reduce the risk of the pressure on an endpoint (e.g., work is conducted at a time of year when the risk to fish and fish habitat (e.g., vulnerability) is reduced. Timing windows can also act to reduce the strength of links along the entire pathway of effects.

Timing windows are a mitigation measure that define periods in the year when work can occur with reduced risk of negative impacts on fish and fish habitat, and consequently, critical life processes of fish (e.g., spawning, migration, natal and rearing, feeding, and refuge use) (Figure 2). Also called environmental windows or work windows, and sometimes referred to by their complement - restricted activity periods, which define elevated risk periods when activities should not occur. Timing windows are not used to mitigate pressures that are permanent or are sustained in the long term (press perturbations) but are imposed to reduce harm associated with pressures occurring at specific periods within the yearly cycle of a fishes' life processes. In this way, timing windows mitigate a temporal or seasonal component of the pressure PoE diagrams, and the responses of endpoints like mortality and the habitats' capacity to support life processes of fish.

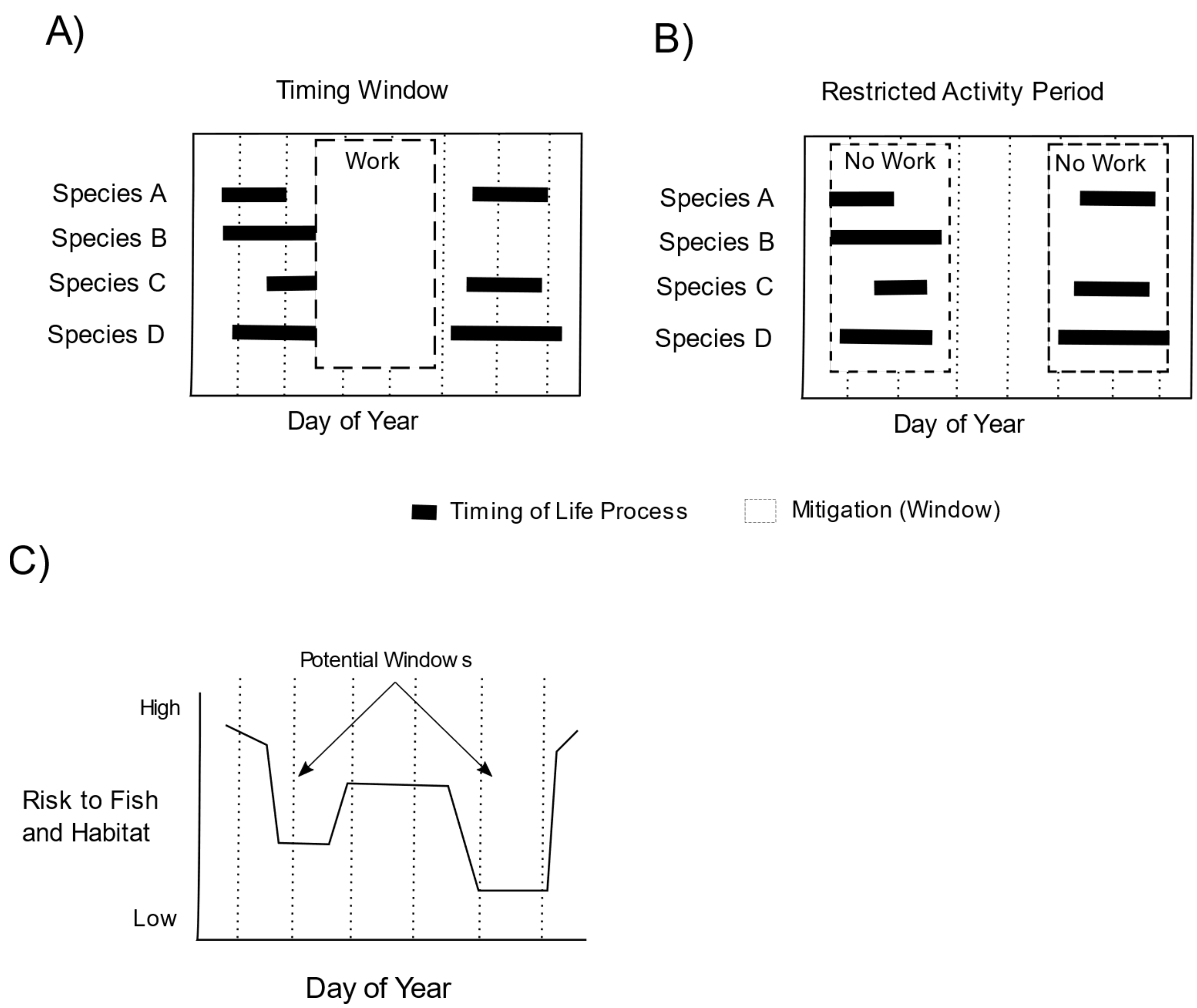

Figure 2. Schematics illustrating key timing window concepts. A) A timing window designates the time that reduces the risk of WUAs. For example, the timing window does not overlap with the timing of species life processes for several species that are of interest for management. B) A restricted activity period designates the time when risks to species are elevated, and work should not overlap with the timing of species life processes (inverse of a timing window). C) The relationship between timing and the magnitude of risk to fish life processes. Potential timing windows are identified as the time of year when risks from the WUA pressures are lowest. If there is no variability in risk then there are no timing windows.

Timing windows are used to protect aquatic and terrestrial biota, and their ecosystems, internationally (e.g., Wu et al. 2018; Wickliffe et al. 2019). In Canada, timing windows are one of the most frequently applied of the suite of mitigation measures used to protect fish and fish habitat, and they are typically applied with other measures. Timing windows are developed by provincial and territorial resource management departments, Fisheries and Oceans Canada or a combination of both in some jurisdictions. Links to Canadian freshwater timing windows, their location of application, and some information about their use is found on the Fisheries and Oceans Canada website with links to provincial sources. They are also summarized below in Section 4.

The core ideas underlying timing windows are intuitive and are supported by other areas of science and management. The timing of events is a major area of scientific research in many areas of biology and ecology (Forrest et al. 2010; Chuine and Régnière 2017). Life history (the sequence of events related to growth, reproduction, and survival within an organism's lifetime) has a principal place in the discipline of fish ecology (Roff 1984; Winemiller 2005), and a key role in the science that informs fish and fish habitat management (Winemiller 2005). Windows are used as a provisional tool (e.g., closures) in fisheries management to respond to short term variability in the environment. For example, a warm water protocol is in place in several New Brunswick rivers to manage recreational fishing activity and reduce risk of mortality at times when temperature exceeds the physiological limits of fish (e.g., Atlantic Salmon (*Salmo salar*)) (Breau et al. 2012). However, it can be challenging for science and management to define timing windows using appropriate information and to determine if they are effective at mitigating harm to fish and fish habitat.

The effectiveness of a mitigation measure or operational control can be defined by whether the measure produces the expected (or intended) outcome when it is applied (Cormier et al. 2017). An effective timing window will reduce risk of harm from WUAs on fish and fish habitat within a geographic area and period defined by the ecology of the target species or habitat. Defining effective timing windows is challenging and requires scientific information that considers phenology (i.e., the study of the timing of natural events (Mundy and Evenson 2011)), habitat and life processes, as well as the temporal changes in vulnerability of fish and fish habitat to WUA pressures. The intent of timing windows can thus vary. Nevertheless, intent should map to policy objectives and be clearly stated so that effectiveness can be tested. For practitioners, applying effective timing windows is important to mitigate WUA pressures and to ensure project compliance with the *Fisheries Act*. Effective mitigation is required to achieve the broader goals of conservation and protection of fish and fish habitat in Canada. However, it is unclear what is known about the effectiveness of timing windows.

The FFHPP is seeking advice on the use of timing windows as a mitigation measure. Timing windows vary among provinces and territories in their characteristics (e.g., spatial scales) and in the intent of windows to protect a diverse assemblage of species, life processes, and habitats. Consequently, there is interest in examining the various approaches used across Canada to develop and implement timing windows. The FFHPP is also regularly faced with requests for WUAs to occur outside of existing timing windows. These decisions should be made with supporting scientific information (which may include considering additional mitigation measures) to reduce harm to fish and fish habitat, and yet there is currently limited guidance for what to consider when creating, modifying (e.g., extending), and applying timing windows. There is considerable complexity involved in developing this guidance as the demands of fish and fish habitat are changing – our ecosystems and societies are not static (Carpenter et al. 2011; Arlinghaus et al. 2015). This means that management actions based on experience may not provide the desired outcome in the future.

In this document we attempt to maintain consistency in terms of terminology and guidance with recent CSAS processes. Advice sought in this process may be used to develop a risk-based framework and so we consulted the FFHPP and previous CSAS documents for information on risk. Our approach includes reference to WUAs, pressures, and the endpoints for fish and fish habitat. However, for a review of all the of effects that potentially serve as rationale for timing windows we refer readers to the recent PoE CSAS materials (Brownscombe and Smokorowski 2021; DFO 2021). For the purposes of this document, rationale are reasons or logical bases that are used to make or modify a timing window and could be used to assess the efficacy of timing windows. We also note that the creation and modification of timing windows may consider socio-economic factors, such as the relative cost of activities or work safety concerns; however, we only briefly mention these considerations.

1.1. PURPOSE AND OBJECTIVES

The purpose of this research document is to address a request by the FFHPP for science advice on the use of timing windows as a mitigation measure. Our goal is to provide a document that functions as a step in the process of building a state of knowledge on the use of timing windows. We aim to provide advice on the science involved to inform their creation and modification and to assess their effectiveness. To this end, this document addresses three main objectives.

1. Review and synthesize examples of the use of timing windows to mitigate impacts to fish and fish habitat. This review will assist in the development of new timing windows, or the refinement of existing ones, and their application. The review may include, but is not limited to:
    a. Scientific studies that provide the ecological rationale for the use of timing windows, effectiveness studies, and frameworks or decision tools that contributed to the development of timing windows.
    b. Considerations and rationale used by other agencies (i.e., other governments and organizations) that may have contributed to the development, application, and evaluation of timing windows.
2. Develop a standardized nationally applicable set of criteria and/or scientific principles that should be considered in the development of a risk-based framework to guide the creation of effective timing windows, modification/refinement of existing timing windows, and their use.
3. Provide advice on the design of studies to evaluate the effectiveness of timing windows. This may include research, monitoring, or modelling approaches.

To address these objectives, we: (1) review the timing windows literature available in a core database and search engine, as well as via North American government websites with specific focus on trends in the type of studies being undertaken and information related to frameworks, rationale, and evaluations for effectiveness; (2) develop a standardized set of criteria to inform creation or modification of timing windows, including a conceptual approach that outlines three key areas of consideration: fish life processes, characteristics of WUA pressures, and habitat characteristics; and (3) provide advice on design of studies and monitoring that can assess the effectiveness of timing windows based on a three-tiered approach that includes studies focused on the probability of exposure to a WUA pressure, the consequences of exposure for life or habitat processes, and population-level effects.

2. RISK AND RISK MANAGEMENT IN A TIMING WINDOWS CONTEXT

The term risk is used throughout this document in our discussion of timing windows. For this reason, we provide a short stand-alone section to define risk and a few components of the risk management process before we begin Objective 1. This section will serve as a reference related to risk for later discussions. Risk applied to environmental decision making is a relatively young field, with more formal application in risk assessment gaining momentum in the environmental protection agency in the United States in the late 1970's (About Risk Assessment). There are many definitions of risk, but typically these definitions can be understood in two ways (Bradford et al. 2015): (1) Definitions about probabilities and the consequence. What is the probability an event will happen and the consequence of this event? (2) Definitions about uncertainties related to the outcome of future events. What are the uncertainties in the outcomes of an event that will happen? What is the magnitude of the consequence? Both definitions are useful for considering risk in relation to timing windows.

Timing windows can be defined by determining how risk varies with time and considering a risk tolerance level that is acceptable to management. How risk changes through time is determined through a risk assessment (Figure 3), which typically will include a risk analysis. This is the step in the risk assessment process where science is required and where data are necessary to estimate risk. Determining the risk tolerance level typically falls under risk management (treatment), a management activity that involves decision-making. All these activities will be guided by a broader risk management process (Figure 3; DFO 2015).

Risk for timing windows can be determined in diverse ways and for different purposes. The desired result of a risk assessment might be knowing whether a timing window will reduce the effects of a WUA on a population. Alternatively, the objective may be an estimate of the probability that a pressure might coincide with an environmental condition or life process and expose fish or fish habitat above the acceptable tolerance level. Timing windows have been used to reduce the risk of harm by avoiding exposure of fish and fish habitat to pressures during periods where the consequences for fish are elevated. FFHPP applies a risk management approach to decision-making for management measures, which includes timing windows (DFO 2019a). While a risk based framework is yet to be developed specifically for timing windows. A framework may consider:

1. a broader risk assessment process;
2. alignment with policy objectives;
3. existing risk analysis frameworks, risk management tools (e.g., pathways of effects diagrams), and indicators;
4. producing an estimate of risk that can be evaluated against a tolerance level in risk management (treatment);
5. continuous improvement to understand risk (research and monitoring).

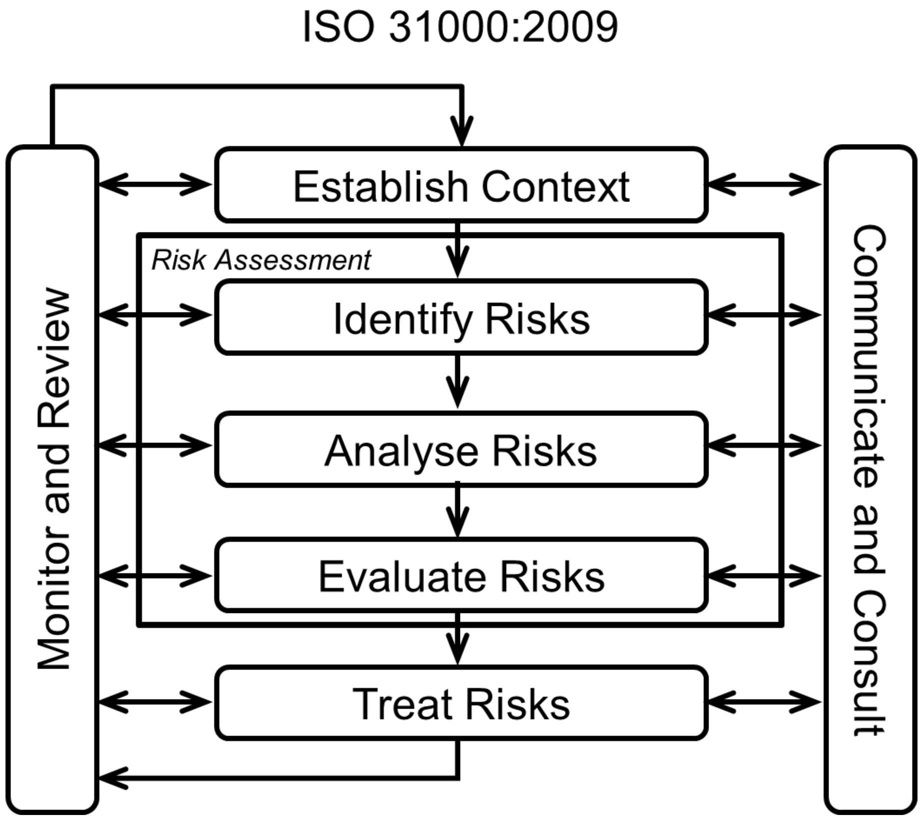

Figure 3. Taken From DFO (2015). A schematic diagram showing the structure of a Risk Management Framework following ISO 31000 guidelines. Three levels are highlighted in risk assessment, identification, analysis, and evaluation. Assessment is followed by risk treatment. A key component of the diagram is the continuous improvement cycle that involves monitoring and review. This may include assessing the effectiveness of program instruments (e.g., mitigation measures).

3. REVIEW OF TIMING WINDOW LITERATURE

We conducted a literature review to determine what is known about the use and effectiveness of timing windows. Our review followed an abridged version of a systematic review following the methods of literature reviews published in recent CSAS documents (see Braun et al. 2019; Caskenette et al. 2020). The review included the following steps: (1) develop a list of search terms; (2) identify key databases and search them with search terms; (3) assess search comprehensiveness; (4) screen documents using eligibility criteria; and (5) categorize documents by their content (See below).

3.1. METHODS

To develop our search terms, we first conducted a cursory search in Google Scholar using key terms from discussions with steering committee members. We also used the recent PoE CSAS as a source of key terms for WUAs and pressures that could potentially be mitigated with timing windows (Brownscombe and Smokorowski 2021). Search terms were organized into five categories: (1) Organismal; (2) WUA; (3) Pressures; (4) Habitat; and (5) Mitigation. These categories were linked with the “AND” operator or were combined into one category as we developed our search strategies (see Appendix B for search terms). Terms within each category were combined using the “OR” operator.

Web of Science and Google Scholar were searched in October/November 2021. Web of Science was searched directly through the website and the search terms were combined to develop search strings using “AND” and “OR”. The software “Publish or Perish” was used to search Google Scholar (e.g., Hodgson et al. 2020), using the same search strings as those conducted in the Web of Science. This tool was set to return the first 1000 search items. Different search strings (Appendix B) were used to complete 15 paired searches for Web of Science and Google Scholar.

We focused a secondary search on six government databases that included the Federal Science Libraries Network and five United States government sites (See Figure 3). These were also completed in October/November 2021. Each database was searched using combinations of terms used in the Web of Science and Google Scholar searches. However, the number of search terms was restricted in some of these databases and as a result the specific set of searches differed. 27 searches were completed using government databases.

Literature was screened in two stages: (1) title and abstract and (2) whole text. Two reviewers performed quick consistency checks at the title and abstract level. Duplicates were removed at each step in the literature search. Based on our broad objectives, documents on the development (including rationale), use and application, and evaluation of timing windows were included in our results. We had an unmanageable number of papers that included pressures generated by WUAs and the effects on different fish species/stages. Due to this, the final list of papers included in the review only included documents that specifically mentioned timing windows, a synonym or a management application that matches with the definition of timing windows. Conference abstracts, presentation slides and specific project review that only include the specific timing window used were not included. To ensure that our collection of articles was comprehensive, as a last step in our search we checked reference lists of the core set of papers against the same criteria, and any additional papers found were included in the review.

3.2. RESULTS

3.2.1. Literature Search and Extraction

A search of Web of Science and Google Scholar returned a total of 22,095 documents, after screening these documents for title and abstract, 288 were retained and this was reduced to 54 documents for the review after removal of duplicates. The government database searches produced 6,880 documents, with a total of 58 documents retained after title, abstract, full text screening, and duplicate removal. The total for all databases combined, after duplication removal, was 92 with an additional 18 documents obtained from the references of these documents. Once the process was complete, we retained 110 documents for the review, representing all the documents in our search that included a reference to timing windows (Figure 4).

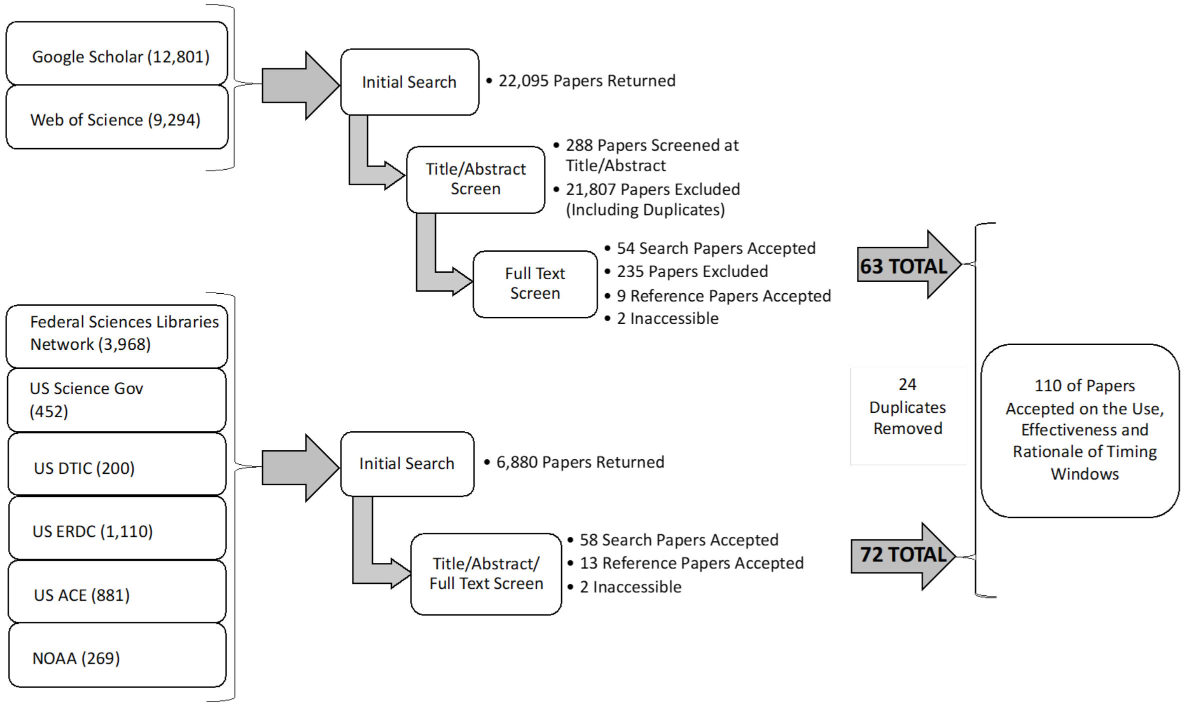

Figure 4. The workflow diagram for the literature review process and number of screening results.

To capture the available information on timing windows we extracted information from all 110 papers. From each document we extracted several pieces of information including data on the type of document/study, the date, the location, ecosystem type, WUAs, pressures, organisms (species) mentioned, life process or stage, the type of timing window, and whether there was any consideration of effectiveness. A list of the literature review documents can be found in Appendix B.

3.2.2. Timing Windows Literature Trends

In this section we present trends and patterns from the literature review on timing windows, and we expand on three areas of interest based on the science advice request: (1) rationale for timing windows; (2) evaluation of timing windows; and (3) timing window frameworks. In doing so, we aim to provide a "state of knowledge" based on available material on the use of timing windows as a mitigation measure.

Literature on the use of timing window as a mitigation measure in resource management has existed for several decades. The earliest document retained in our search is from 1984, one of only four documents from the 1980's (Figure 5). This aligns with the approximate 40-year history of use of timing windows in the United States (National Research Council (NRC) 2001), and adoption later in other places like Canada, Australia, and Europe. The number of documents retained on timing windows monotonically increased each decade until the present, with 50 of the total 110 documents retained from 2011-2020. Much of the available documentation on timing windows is in the form of reports written by government and consultants; we retained only 19 peer reviewed science journal articles on timing windows. Trends in the material found in these documents are expanded upon in the following sections: WUAs, life processes, ecosystem types, study type; and summarized in Figure 6.

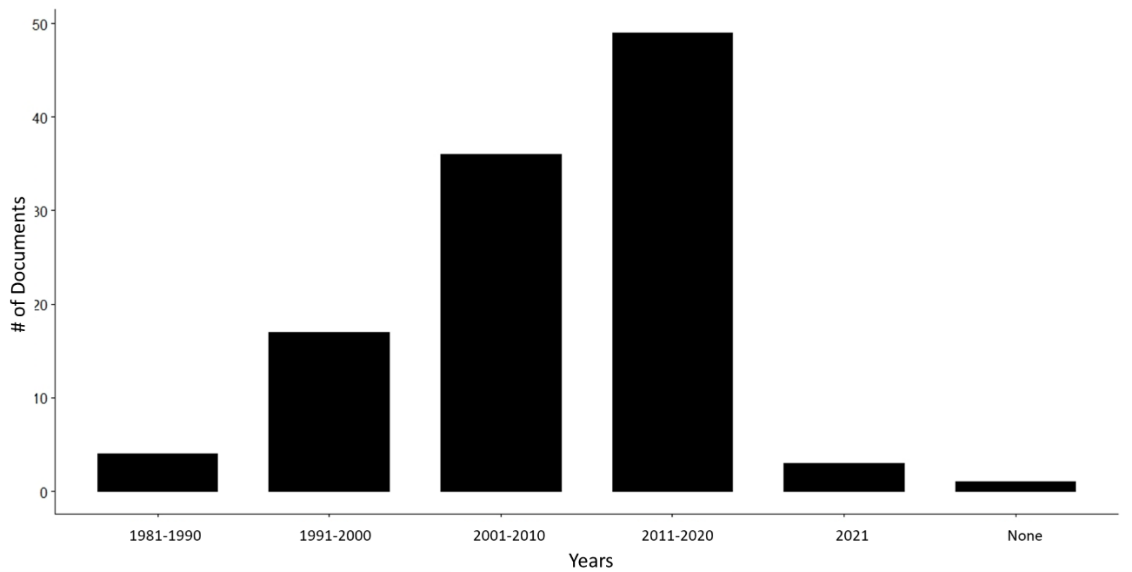

Figure 5. A bar plot of the timing windows literature summarizing the number of documents that were retained in our search by decade of publication. Note one document had no publication date.

3.2.2.1. Ecosystems

We found reference to several different ecosystem types, including freshwater, coastal and estuary, and marine. To gain a general understanding of the prevalence of different ecosystem types in the literature we noted the number of documents that reference each ecosystem type. If a document discussed more than one type of ecosystem an observation was added to each of the appropriate categories. Some documents discussed more than one type of ecosystem and others did not explicitly discuss any specific type. Estuarine ecosystems (39) were mentioned the most, followed by marine (25) and freshwater (25). Many documents reviewed did not explicitly name an ecosystem type (32) or just referred to coastal ecosystems (Figure 6A). The papers that did not specify an ecosystem type were usually government technical documents that discussed dredging or other WUAs in general and did not specify their use in an ecosystem.

3.2.2.2. Works, Undertakings, and Activities (WUAs) (i.e., dredging)

The most striking finding of our review was the dominance of dredging documents in the timing windows literature. Dredging is the term given to the activity of underwater material extraction that is used to create and maintain navigation channels for watercraft. There are several potential pressures generated by dredging that may pose a risk of harm to fish and fish habitat including death of fish by entrainment (e.g., direct uptake of aquatic organisms by the suction field of the dredge; Reine et al. 1998a), and suspension and deposition of fine sediment during spawning that can disrupt spawning behaviour and lead to egg mortality (Levine-Fricke 2004; Connor et al. 2005; Rich 2010; Kjelland et al. 2015). We found that of the 110 studies and reports that we retained on timing windows, 100 referred to dredging (Figure 6B). The association between timing windows and dredging in the documents reviewed appears to be a consequence of an interest from the United States Army Core of Engineers (USACE) associated with several factors related to dredging operations including a tradeoff between environmental protection versus scheduling and costs associated with dredging activities. It was reported, for example, that the USACE spends millions of dollars accommodating timing windows in dredging operations (Dickerson et al. 1998).

3.2.2.3. Life Processes

Different life processes were discussed in the literature including spawning, migration, natal (eggs), rearing (early-life phases), feeding, and refuge use. Except for refuge use and feeding, the number of documents that discussed each life process was similar. Out of these, natal and rearing were discussed the most (38 and 39) in the literature (Figure 6C). The reason for this may be because of the assumed vulnerability of eggs and larvae to WUA pressures associated with dredging (e.g., sedimentation). Also, early life studies (e.g., eggs or larvae) are typically easier to conduct.

3.2.2.4. Categories of Study Types

To characterize the literature on timing windows, documents were separated into five categories: (1) Frameworks; (2) Standard research or modelling on the development, use, evaluation, and rationale of timing windows; (3) Reviews on studies and models for the development, use, evaluation, and rationale of timing windows; (4) More than one category; and (5) Other. Category 4 refers to literature that does not fit into one specific category. It could, for example, include reviews of standard research but also include some type of framework. Category 5 (Other) refers to studies that do not fit into any of the other categories.

Standard research and modelling had the greatest number of documents (41). This category included peer reviewed journal articles as well as government documents or workshops. Category 5 was the second highest category containing one third of the documents (31) (Figure 6D). Some of these papers include US government technical notes or dredging workshops that discuss opinions on economic consequences of environmental windows with limited mention of ecological considerations.

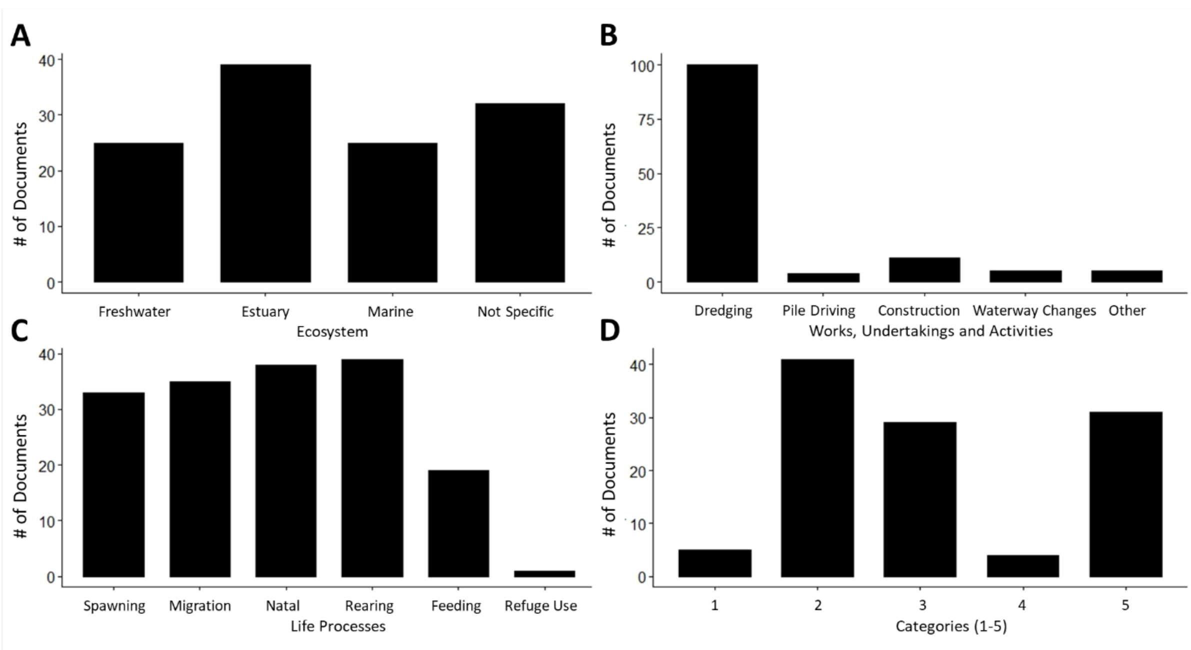

Figure 6: Bar plots summarize material reviewed in the timing windows literature search. Documentation is broken down by four categories: (A) Ecosystem types connected to timing windows; (B) The works, undertaking and activities mentioned in material; (C) Life processes mentioned in material; and (D) The type of information documented (study type). Study type categories include: (1) Frameworks; (2) Standard Research or Modelling; (3) Reviews; (4) More than one category; and (5) Others.

3.2.3. Review of Rationale Studies for Timing Windows

The fundamental premise of timing windows is that there are periods within the annual cycle of events in ecosystems when organisms and their habitat are less vulnerable to anthropogenic activities (i.e., WUAs). If the vulnerabilities of fish, of their habitat or of the pressures that harm fish and fish habitat do not vary within the annual cycle, such as by season, then there is little a timing window will do to mitigate harm. This premise is discussed in several timing window documents where identifying periods of high and low vulnerability of species to WUA pressures was part of the process of creating timing windows (NRC 2001). A few documents also recognized that timing may influence variability in the pressures produced from WUAs. However, there is a lack of research studies in the timing windows literature that address this temporal component explicitly.

The research materials reviewed were typically conducted to establish or challenge the pressure and effect relationships for a species life stage used to rationalize a specific timing window. The timing component to these studies was captured by the natural variance in life stages/processes within a yearly cycle. This focus may be due to the predominance of dredging studies in the literature since many studies focused on a life process or stage that was specifically connected to pressure from dredging activities. For example, Pacific Herring (*Clupea pallasii*) are typically not prevalent in the nearshore where dredging occurs aside from limited periods of the year when the species is aggregated to spawn and for early life periods (i.e., eggs and larvae) (Suedel et al. 2008). Research studies for this species are thus focused on an element of exposure during a limited period, such as the effect of suspended sediment on eggs (Griffin et al. 2009; Griffin et al. 2012).

In the sections that follow we review timing windows rationale research from the literature search. The material reviewed is useful to understand the state of knowledge targeted to timing windows; however, the breadth of material reviewed is limited. We have taken a broader approach to identify rationale for timing windows in Section 6 where we address the suitability and vulnerability of life process in the context of Objective 2. The review below focuses on different life processes and stages for fish, including early life phases (natal, rearing, feeding), adults (spawning, migration, feeding) (Levine-Fricke 2004; ECORP Consulting Inc. 2009; Rich 2010; Kjelland et al. 2015) and other aquatic species.

3.2.3.1. Fish

3.2.3.1.1. Natal and Rearing

Early life phases (eggs and larvae) of fish have variable responses to pressures. For example, Walleye (*Sander vitreus*) eggs and fingerlings were found to be tolerant to sedimentation (Suedel et al. 2012; Suedel et al. 2014), but higher concentrations of sediments may reduce egg viability in some cases (Suedel et al. 2014). Early life phases of Pacific Herring, after 2 hours post fertilization, also did not appear to be negatively affected in some studies, (Griffin et al. 2008; Griffin et al. 2009; Griffin et al. 2012) but other studies found increased egg mortality and reduced larval growth and development (Levine-Fricke 2004; Connor et al. 2005; Ogle 2005). Studies have documented variability and species-specific responses to WUAs and pressures (Berry et al. 2011; Suedel et al. 2017). This could be, in part, because many of the studies reviewed were lab-based; the applicability of these findings in the wild is unclear.

3.2.3.1.2. Feeding

Literature on the feeding habits of fish is limited in the context of timing windows. Most of the literature is comprised of review documents and workshops that briefly discuss feeding, with little to no reference to peer-reviewed scientific studies. The presence of suspended sediments and increased turbidity, which can result from dredging, reduced feeding for many species, like salmonids, Largemouth Bass (*Micropterus salmoides*), and Northern Pike (*Esox lucius*) (Levine-Fricke 2004; Connor et al. 2005; ECORP Consulting Inc. 2009; Kjelland et al. 2015). However, material reviewed suggests there is also a lot of inconsistency for some species (Levine-Fricke 2004; Connor et al. 2005; ECORP Consulting Inc. 2009; Kjelland et al. 2015). The mechanisms were also unclear but could be due to visual changes, increased avoidance by prey, or other factors (Kjelland et al. 2015).

3.2.3.1.3. Spawning

WUAs and associated pressures were found to affect fish spawning activities (Rich 2010; Kjelland et al. 2015). Some of the literature on spawning focused on reproductive success. The success can be influenced by changes in fertilization, avoidance of spawning habitat, degradation and burial of spawning grounds or changes in spawning behavior (Levine-Fricke 2004; Ogle 2005; Rich et al. 2010). For example, dredging and associated sedimentation degraded the spawning habitat of Delta Smelts (*Hypomesus transpacificus*) (Levine-Fricke 2004).

3.2.3.1.4. Migration

Timing windows literature suggests that WUAs and related pressures result in undesirable effects on fish migration (Levine-Fricke 2004; ECORP Consulting Inc. 2009; Rich 2010; Wickliffe et al. 2019) and yet, some species move through WUA areas undisturbed (Balazik et al. 2020; Balzaik et al. 2021). Other studies highlighted that migration could be impacted (Rich 2010; ECORP Consulting Inc. 2009; Levine-Fricke 2004). Examples include Coho Salmon (*Oncorhynchus kisutch*), Arctic Grayling (*Thymallus arcticus*) (Levine-Fricke 2004) and Atlantic Salmon (*Salmo salar*) (ECORP Consulting Inc. 2009). The literature reviewed consists of a small number of studies that are mostly field based, research reviews, and government documents. Physical conditions as well as waterway restrictions may contribute to differing migration impacts (ECORP Consulting Inc. 2009), although environmental context is not extensively researched.

3.2.3.2. Consideration of species other than finfish

The literature search was dominated by documents about finfish, but some material considered other organisms including: coral, seagrasses, oysters, sea turtles, and mammals. Early life and adult phases of some species of coral can be vulnerable to sediments, reduced light for photosynthesis, and water quality changes (McCook et al. 2015). Sea grass material all focused on dredging and related pressures associated with sediment, physical damage, light reduction, and water quality. The effects of these pressures can be severe but are dependent on species and ecosystems (McCook et al. 2015; Fraser et al. 2017; Wu et al. 2017). Oyster vulnerability varied based on species, pressures, and/or life phases. Conflicting information was found concerning entrainment of oysters due to dredging (LaSalle et al. 1991; Carter 1986; Reine et al. 1998a). Suedel et al. (2015) described eastern oysters as tolerant to sediment. Sea turtles and dredging impacts were the focus of some government technical reviews and workshops. Sea turtles were affected by dredging entrainment (Dickerson and Nelson 1988; Dickerson et al. 1995; Reine et al. 1998a; Dickerson et al. 2004), but vulnerability to entrainment varied among turtle species depending on how and when they used the dredging areas (Dickerson et al. 1995; Reine et al. 1998a; Dickerson et al. 2004). Mammal behaviour can be affected by dredging-related noise. Dredging can also indirectly affect mammals through effects on their prey (Todd et al. 2015).

3.2.3.3. Habitat and Ecosystem

While the material found in our review discusses species and life phases, it does not directly discuss studies that could inform the necessity for timing windows in specific habitats or ecosystems. The ecological context within different habitats and ecosystems (e.g., temperature regime, habitat complexity) is a plausible explanation for some of the variable results found in the research highlighted above. This important caveat is discussed in several papers that were reviewed (ECORP Consulting Inc. 2009; McCook et al. 2015) and the need for additional research on habitat and ecosystem processes was also highlighted (NRC 2001).

3.2.4. Evaluation of Timing Windows

Evaluation is an important part of developing effective timing windows that function as they were intended. A considerable number of documents in our review discuss the need for more scientific evaluation of timing windows. This statement is supported by our review as we found few documents that applied a scientific approach to evaluate timing window effectiveness. Most of these studies focus on dredging and its effect on fish rather than habitat, using indicators such as the presence of fish, fish mortality, or sub-lethal impacts like behaviour (Reine et al. 2014; Chapman et al. 2019; Balazik et al. 2020). Importantly, despite variable approaches to timing window evaluation, we found no examples of high intensity field experiments measuring population level consequences. Hereafter, we present examples of field research and alternative approaches (e.g., models) to review material on the effectiveness of timing windows.

Two observational studies concluded that the defined timing windows were not effective at reducing risks to fish. First, Chapman et al. (2019) suggest that timing windows are not effective because their study found high numbers of Green Sturgeon (*Acipenser medirostris*) at dredging locations and dredging disposal sites in San Francisco Bay Estuary during the timing window. Second, trawl surveys conducted during three periods (summer, fall, winter) in Little Bear Creek, Lake St. Clair, found high numbers of fish, including Pugnose Shiner (*Notropis anogenus*) a species at risk, within the fall timing window, and further suggested that current windows may leave rearing habitats at risk (Barnucz et al. 2015).

Recently published acoustic telemetry studies evaluated a restricted activity period proposed to protect the migration of endangered Atlantic Sturgeon (*Acipenser oxyrinchus oxyrinchus*) from dredging in a 12 km long, 4 km wide section of the lower James River, Virginia (Reine et al. 2014; Balazik et al. 2020). A pilot study recorded data on five fish and reported no mortalities related to dredging (Reine et al. 2014). However, the authors noted elevated mortality risk as fish used benthic habitats where they are more susceptible to the dredge. Balazik et al. (2020) expanded this study in the same location, including 98 additional tagged sturgeon. The authors question the requirement of a restricted period in this situation based on their result of no mortalities of tagged sturgeon and no behavioural changes in sturgeon between periods of dredging and no dredging. The authors caution that their results may not apply to smaller water bodies.

Field studies are more commonly used to evaluate effectiveness, but models and other approaches can be an important complement. For example, one non-peer reviewed report presented an approach to graphically assess the effectiveness of a restricted activity period using catch data from a fishery (Rogers and Nicholson 2002). This kind of research that provides an approach to develop better objectives and criteria for determining effectiveness is rare but ought to be useful for timing windows. Another study used Bayesian Belief Network (BBN) models to show that the resilience of seagrass beds at ports around the globe could be preserved by utilizing timing windows for dredging activities (Wu et al. 2017). A third example compared timing windows for specific dredging activities using a set of three models that: (1) assess the temporal and spatial extent of sediment plumes (SSFATE); (2) use the theoretical plumes to determine the exposure of fish life stages (SSDOSE); and (3) to link exposure to fish population dynamics (FISHFATE) (Clarke et al. 2003). The assumptions of different approaches should be considered, as should the resource demands required. Simpler approaches than those that require multiple models and considerable data inputs are preferred for most situations, but regardless of the approach used, clear and specific objectives are critical to assessing effectiveness of a timing window.

3.2.5. Frameworks

A review of timing windows frameworks is a crucial part of our first objective, as the information may be informative for the development of a standardized framework for timing windows at DFO. Our literature search retained five documents that present frameworks for the creation or modification of timing windows. These documents varied from peer-reviewed science journal articles (e.g., Suedel et al. 2008), to government documents (e.g., LaSalle et al. 1991), and multi-organizational workshop reports (e.g., NCR 2001). Despite a limited amount of material, we provide a summary of documents that were written with the intent of supporting the development of a framework for creating or modifying timing windows.

The motivation for the development of frameworks for timing windows was similar among documents. Timing windows can be a valuable management measure to protect biological resources. However, there is tension concerning whether many timing windows are producing their intended outcome. These concerns were raised from the perspective of the protection of biological resources like fish but also out of consideration for stakeholders (NCR 2001; Burt 2002; Burt and Hayes 2004; Suedel et al. 2008). Framework documents, and other materials in our review suggest that the scientific evidence used to create some timing windows is inconsistent, outdated, or non-existent (LaSalle et al. 1991; Reine et al. 1998b). Others suggest that socio-economic factors are not well considered (NRC 2001; Suedel et al. 2008). Therefore, it is argued that frameworks are required in many instances to guide the process for creating and modifying timing windows, to improve consistency and to ensure that applied timing windows are based on the best available information.

Typically, frameworks for timing windows involve a multiple step process that considers the cycle of the pressures generated by a particular activity (often dredging), the vulnerability or consequences for organisms, and a step that involves making a management decision about whether a timing window is required, or about the specific time of year that the timing window is most appropriate (LaSalle et al. 1991; NCR 2001). Some frameworks were developed to mitigate a specific project, and the associated pressures that were expected to affect a species or defined set of species at a particular location (e.g., dredging in San Francisco Bay) (Connor et al. 2005; Suedel et al. 2008). Other frameworks have been developed for more general applications over broader geographic areas, for example, at the state level (e.g., North and South Carolina, Wickliffe et al. 2019). These consider numerous human activities and pressures as well as a wider range of biological and ecological considerations.

Frameworks reviewed were different in terms of their complexity and have advantages and disadvantages. LaSalle et al. (1991) is an example of an earlier developed framework that has a small number of steps and is directed toward creating a timing window for dredging projects. First, the framework calls for identifying the set of pressures related to fish survival or a life process (e.g., entrainment by dredges). This framework applies a three-step decision process to develop timing windows. Other frameworks included stepwise processes like LaSalle et al. (1991) but often added more or different steps, and more detail, which may require a greater investment of resources. For instance, NCR (2001) presents a six-step process that can be completed within an annual cycle (revisited in future years) to guide setting, managing, and monitoring timing windows. This framework considers organism life history, impacts, stressors and thresholds, and potential technological solutions. It also includes initial steps to: (1) form a working group that involves stakeholders; (2) evaluate options for technological ways to reduce pressures; (3) consider the socio-economic factors; and (4) plan monitoring of the proposed activities. Suedel et al. (2008) took a different approach compared to the frameworks mentioned above. This study first conceptualized the problem and then laid out a framework by working through a well-known case study. One advantage of the Suedel et al. (2008) framework is that it provided a description of a software tool and process used to weigh different options for windows. Other frameworks outlined the steps of the process with little detail on the risk assessment or treatment. Frameworks from the timing windows literature are a useful place to start, however, a broader search for frameworks and tools used in risk assessment is recommended.

3.2.5.1. Tools

An exhaustive review of the range of tools or analysis that could be used to inform timing windows is beyond the scope of this document. Here we review the tools that have been identified in the timing windows framework material. The frameworks reviewed tend to provide insight into the steps to the process of creating or modifying timing windows and the kinds of data or research questions that could be included. Few documents provide particulars of the kinds of risk analyses or decision analyses that were to be applied (for exception see Suedel et al. 2008). However, framework documents included diagrams of the decision process, conceptual diagrams, or examples of data collection tools and qualitative checklists that can be used in the field (NCR 2001) to aid in the development of physical and biological models (Burt and Hayes 2004). For example, some applications that are specific to mitigating dredging operations adopt dynamic fish population models to assess the vulnerability of different life stages (Meester et al. 2001; Rainwater et al. 2016, 2017). The type and complexity of the tool may depend on many factors, not limited to the size and complexity of the area that is being considered for the window, the activities and pressures that are being considered, the availability of data, and the resources available (Wickliffe et al. 2019).

Research on decision tools for timing windows can be helpful to inform the development of frameworks and the risk analysis and treatment processes of deciding on a timing window. There do not appear to be many tools used for decision-making on timing windows. But it is not clear if this perceived gap is due to a lack of tools, or a lack of information published on tools. Some documents mention modelling approaches for decision making but do not provide details on their use. Suedel et al. (2008) emphasizes the incorporation of a risk-based decision tool as a core part of their framework. They use a software application (SMAA-III) that helps users set weights for criteria, incorporates biological, physical (mostly related to pressures), water quality, and cost information into a risk and decision analysis. The entire process was used to compare windows as part of a risk assessment process.

3.2.5.2. Timing Windows and Adaptive Management

Revisiting timing windows is included in some frameworks as a step in the management cycle (NRC 2001). This revisiting step serves as an opportunity to update timing windows based on the latest information. It also serves to update plans to prioritize scientific research, and revisit uncertainties in physical and biological data. This revisiting is critical in light of rapid global change (e.g., climate change) that can alter the composition of aquatic ecosystems and shift the timing of events. Such changes mean that expectations based on experience may not apply to current or future conditions. An adaptive management cycle has been suggested to manage ecosystems in the face of a changing and uncertain environment (NRC 2001). Such an approach is expected to maintain more effective timing windows, however there was a lack of evidence this advice is being used.

3.2.6. Key Considerations

We reviewed the material on timing windows in terms of rational, evaluations of effectiveness, and frameworks. Our review focused specifically on the 110 documents that were retained from our literature search on timing windows. We found that the literature was dominated by reports and government documents, with few peer-reviewed scientific journal articles. More specifically:

- Much of the material reviewed was related to one activity, dredging. Therefore, it is important to remember this trend when considering the information provided in our review, since similar approaches may not be suitable for all WUAs.
- Numerous studies suggest that timing windows are not well supported by scientific evidence and are defined based on practitioner experience.
- Timing windows are premised on the idea that the vulnerability of fish and fish habitat to pressures generated by specific WUAs varies through time.
- Most research focused on the interaction between pressures and impacts on species/life stages and not explicitly temporal variability in vulnerability; however, this temporal aspect is implicit in these studies based on the life stage or process (e.g., whether egg or larvae are being exposed to sediment).
- Few clear evaluations of the effectiveness of timing windows were found in reviewed material, these tend to be field studies, but modelling was also used to identify and compare windows, and one report developed criteria to test effectiveness.
- Frameworks for creation or modification of timing windows include multi-step processes that outline steps for developing a timing window, deciding on a window, and in some cases monitoring. Few framework documents included details on the treatment of data/information, on the risk assessment process or on the final decision-making process.

4. FRESHWATER TIMING WINDOWS IN CANADA

4.1. METHODS

To explore timing windows currently used throughout Canada, an information search was initiated on the *Fisheries and Oceans Canada, Projects Near Water* website. Some provinces have information directly on this website, whereas others provide links to documents that provide information. Information about identified WUAs and pressures, protected life phases, type of window used, fish species protected by windows, spatial and/or biological scales windows are based on, and specific windows were extracted from the website and documents (see Appendices Table SI-3 and SI-4 for the Canadian Summary Tables). Additional searches were required for some provinces (e.g., Nova Scotia, NS). Google searches were conducted for these provinces or territories by using the province in question and “timing windows”, “work windows” or “restricted activity periods”. The information is summarized in Table 1 (See Appendix Table SI-4 for the Canadian Timing Window Sources).

4.2. SUMMARY

Canada is diverse in species and habitats so there are a lot of different situations that will require protection using timing windows. The provinces and territories in Canada use two different mitigation measures: (1) Timing windows and (2) Restricted activity periods. Comparable numbers of provinces and territories use either timing windows (n=6) or restricted activity periods (n=7); however, the provinces are quite diverse in terms of the specific timing windows and restricted activity periods that are used. There are differences in documented protected life processes, species, and their specific timing windows or restricted activity periods (Table 1).

All provinces and territories mention protection of spawning and egg incubation as rationale for timing windows (timing window and restricted activity period). Many other provinces and territories include hatching (AB, NB, NL, NT, NS, NU, SK, YU), with others also including migration (AB, BC), larvae mobility (QC), fry/larval emergence (AB), or other non-specific processes/stages (ON, BC). The fishes protected in each province and territory vary, with many protecting sportfish (See Appendix B). This provides some basis for the differences seen in the provinces and territories. They also provide a broad range of documented WUAs, with some also providing indications of the pressures that were to be mitigated (Table 1).

Provinces and territories are distinct in the types of scales they use for timing windows or restricted activity periods. This includes spatial and biological scales. Spatial scales range from provincial/territorial, regional, subregional and watershed/rivers. Biological scales include spawning periods or thermal guilds, fish groupings and then specific species. Provinces and territories may use just one or a combination of these. For example, the maritime provinces use a single timing window whereas NL uses restricted activity periods for fish species (Atlantic Salmon, Brown Trout) in different regions (mainland, island) and subregions (estuaries/mainstems and tributaries/headwaters) for a total of four unique periods. Alternatively, NU has restricted activity periods based on regions and thermally dissimilar fish resulting in four restricted activity periods. BC has the most complex timing windows, which are set up for different species in watersheds of subregions (22) within larger regions (8). BC has a total of 92 different timing windows with some timing windows being used in different regions, subregions or watersheds (Table 1) (Figure 7).

Table 1. Summary of available information on timing windows and restricted activity periods in Canada. The information presented here was gathered from the Fisheries and Oceans website, documents linked to this website and other relevant online documents. Timing windows are applied to any work in or near water, this table identifies information that is specifically mentioned in the public available information. See Appendix B Section 10.2.4 for the additional online resources used. Note “Identified WUAs” lists specific examples provided in documentation for each Province/Territory and not only to the WUAs where timing windows are applied (e.g. NL documentation doesn’t refer to any specific WUAs but timing windows are applied to any WUA.

Province/ Territory	***Identified WUAs***	***Identified Pressures***	***Window Type***	***Protected Life Stages/Behaviours***	***Spatial Scale***	***Biological Scale***	***# of Unique Timing Windows***
Alberta	Pipeline, powerline, outfall structure, hydrostatic testing, watercourse crossing work	Erosion, sedimentation	Restricted Activity Periods	Migration, spawning, egg incubation and hatching/fry emergence.	Regional (10)	Species	23
British Columbia	Land development, in-stream and in-water works (bank stabilization, bridges, channel maintenance, culverts, restoration, pipeline, utility work), construction modification and deactivation activities on crossings	Depositing sediment, habitat destruction	Timing Windows	Migration, spawning, "other life history stages"	Regional (8)- Subregional (22) - Watershed/Rivers	Species	92
Manitoba	Operation of machinery, clearing shorelines, pipeline work (instream, nearshore construction)	Erosion, depositing sediments into fish habitat	Restricted Activity Periods	Spawning, incubation/ development	Regional (2)	Spawning Times (Spring, Summer, Fall)	6

Province/ Territory	Identified WUAs	Identified Pressures	Window Type	Protected Life Stages/Behaviours	Spatial Scale	Biological Scale	# of Unique Timing Windows
New Brunswick	Operation of machinery, changing structure, depositing/removing sediment, ground disturbance, vegetation and tree removal in watercourse/wetland. Dredging, dams, pipeline, bridges, culverts, land extensions.	Sedimentation, compaction, erosion	Timing Windows	Migration, spawning, egg incubation, hatching, feeding	Provincial	n/a	1
Newfoundland & Labrador	All WUA	n/a	Restricted Activity Periods	Migration, spawning, egg incubation and hatching	Regional (2) - Subregional (2)	Taxonomic Group (Family or Species)	4
Northwest Territories	"In-water or shoreline work", "In-water construction"	"Disturbances or sediment"	Restricted Activity Periods	Spawning, egg incubation, hatching and fry	Regional (3)	Spawning Times (Spring/Summer, Fall, Winter)	4
Nova Scotia	Installation, maintenance, removal of bridges, culverts, wharves/docks, water intakes, utility crossing and dams/water storage. Removing/adding material to watercourses and restoration projects/channel alterations.	Erosion, channel changes, water depth/speed changes, sediment movement and deposit	Timing Windows	Spawning, egg incubation and hatching	Provincial	n/a	1
Nunavut	n/a	n/a	Restricted Activity Periods	Spawning, egg incubation and hatching	Regional (2)	Spawning Times	4

Province/ Territory	*Identified WUAs*	*Identified Pressures*	*Window Type*	*Protected Life Stages/Behaviours*	*Spatial Scale*	*Biological Scale*	*# of Unique Timing Windows*
Ontario	"In-water works"	n/a	Restricted Activity Periods	Spawning, migration and "other crucial life history stages"	Regional (3)	Species	15
Prince Edward Island	Drain, pump, dump, infill, deposit, dredge, excavate or remove soil, water, stone, etc. Construct, repair, remove structures. Operate heavy equipment or a motor vehicle on sediment bed, beach or bank of watercourse or wetland. Disturb, remove, alter ground or vegetation and carry out enhancement activities.	Compaction, increased erosion, sedimentation of fish spawning habitat (smothering of eggs, destruction of resources)	Timing Windows	Spawning, egg incubation and rearing	Provincial	n/a	1
Quebec	n/a	n/a	Timing Windows	Spawning, egg incubation and larvae mobility	Regional (17)	Taxonomic Group (Family, Species)/Species of Interest	22
Saskatchewan	Large vehicle use, plough-in pipeline work it is near or in water. Road construction, drilling, trench-in pipeline, blasting, rock crushing, asphalt batching if it is in or near water.	"Disturbance", sedimentation	Restricted Activity Periods	Spawning, egg incubation and hatching	Regional (3)	Spawning Times (Spring, Fall/Winter)	11

Province/ Territory	*Identified WUAs*	*Identified Pressures*	*Window Type*	*Protected Life Stages/Behaviours*	*Spatial Scale*	*Biological Scale*	*# of Unique Timing Windows*
Yukon	Trenching, drilling and work involving explosives. Altering bed, banks or channel of watercourse. "In stream work", building temporary roads, clearing vegetation.	Erosion, sedimentation and increased runoff, nutrient and contamination influxes, temperature, and flow alterations	Timing Windows	Spawning, egg incubation and hatching	Regional (6)	Species	14

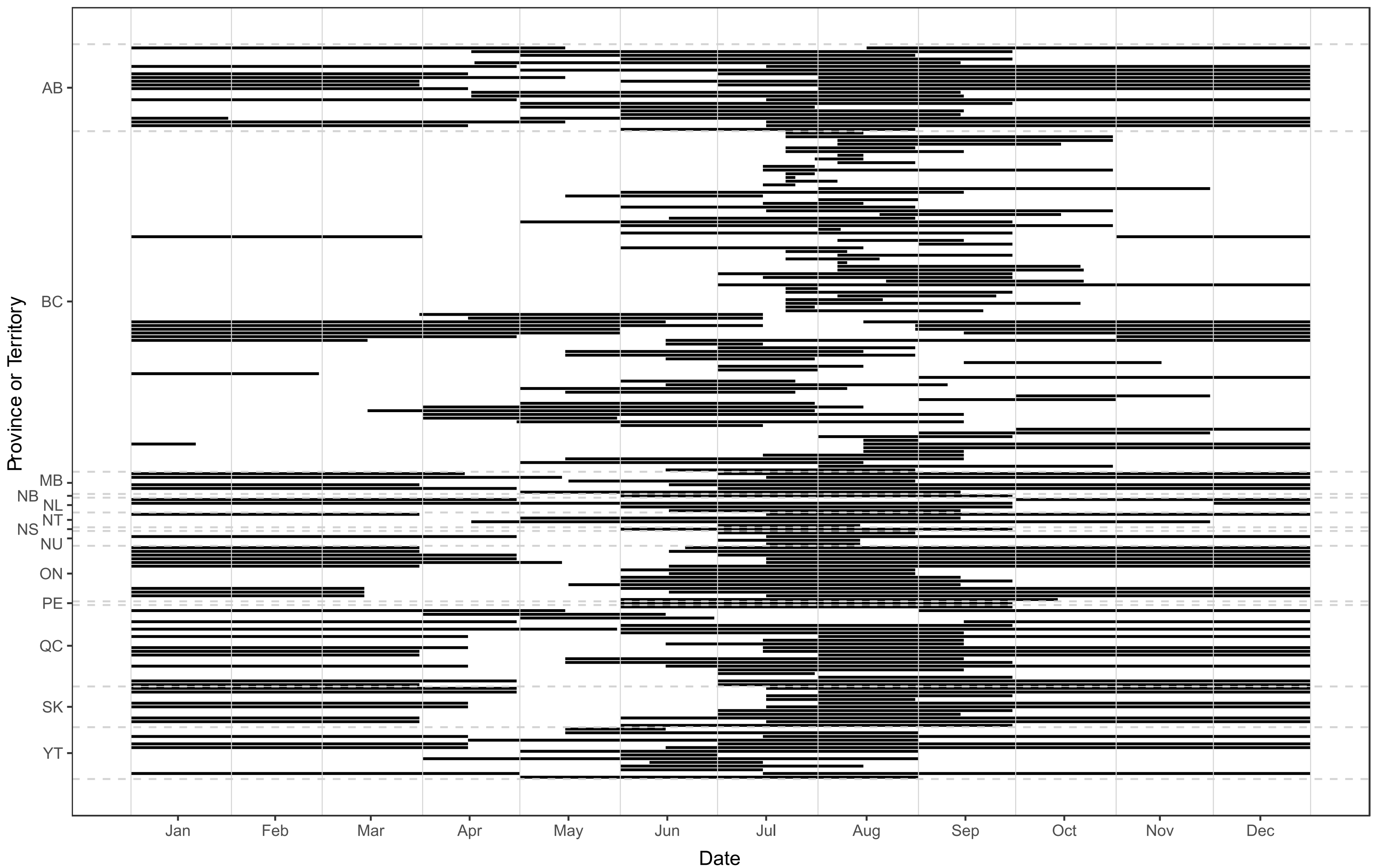

Figure 7. Plot showing the variability of freshwater timing windows within and between Canadian provinces and territories. All times shown here, identified with dark lines, represent times when work is allowed. Please note marine timing windows are not shown in this figure.

Marine windows were not the focus on this review, however the *Fisheries and Oceans Canada, Projects Near Water* website links to information on marine timing windows for BC, QC and the NL document references estuary timing windows. We provide a brief summary of marine timing windows for these provinces in Appendix 10.2.5. Further work will be required to compile a complete summary of marine windows in Canada.

4.2.1. Key Considerations

Our purpose in reviewing the timing windows used in Canada was not to audit the windows, but to gather and summarize the information on the current use of timing windows in freshwater. We did inquire about timing window information in marine environments, but this information was not as readily available and will need to be compiled at a future time. There are a few general observations that can be made.

- The use of timing windows including application of timing windows versus restricted activity periods, the rationale for their use, and their temporal and spatial characteristics differ across Canada.
- Timing windows are used to protect a diverse group of species, spawning is the most common life process identified, and sedimentation is a common pressure to be mitigated.
- A more comprehensive review is required if the kind of information summarized here is used in a scientific context. For example, in developing frameworks, identifying the intent of specific windows, and for prioritizing evaluations of effectiveness. This will require collaboration between DFO and provincial and territorial agencies.
- The resolution of publicly available information is variable across the country. Some material exists, but data sources were often not provided, and details of the process used to define timing windows were not publicly available.
- Finally, it is important to note that we did attempt (although not exhaustively) to identify source material or documents that explain how timing windows in Canada have been developed or defined and were unable to locate this information. Discussions with some practitioners emphasized that some timing windows were developed based on regional knowledge and that they were intentionally conservative (i.e., narrow timing window or broad restricted activity period) to ensure they fully protected the life process of interest.

5. CONSIDERATIONS TO DEVELOP, APPLY AND MODIFY TIMING WINDOWS

To address the second objective, we present scientific rationale and considerations to guide the development, application, and modification of timing windows. These criteria are based on the premise that timing windows require information about how the potential risk from a WUA varies through time (see section 3). Approximating that risk involves several layers of information, which are conceptualized in Figure 8 and then discussed in further detail in subsequent subsections. Specifically, we describe: (1) the timing of vulnerability of fish life processes; (2) characteristics of the WUA and its associated pressures; and (3) characteristics of habitats and environmental conditions.

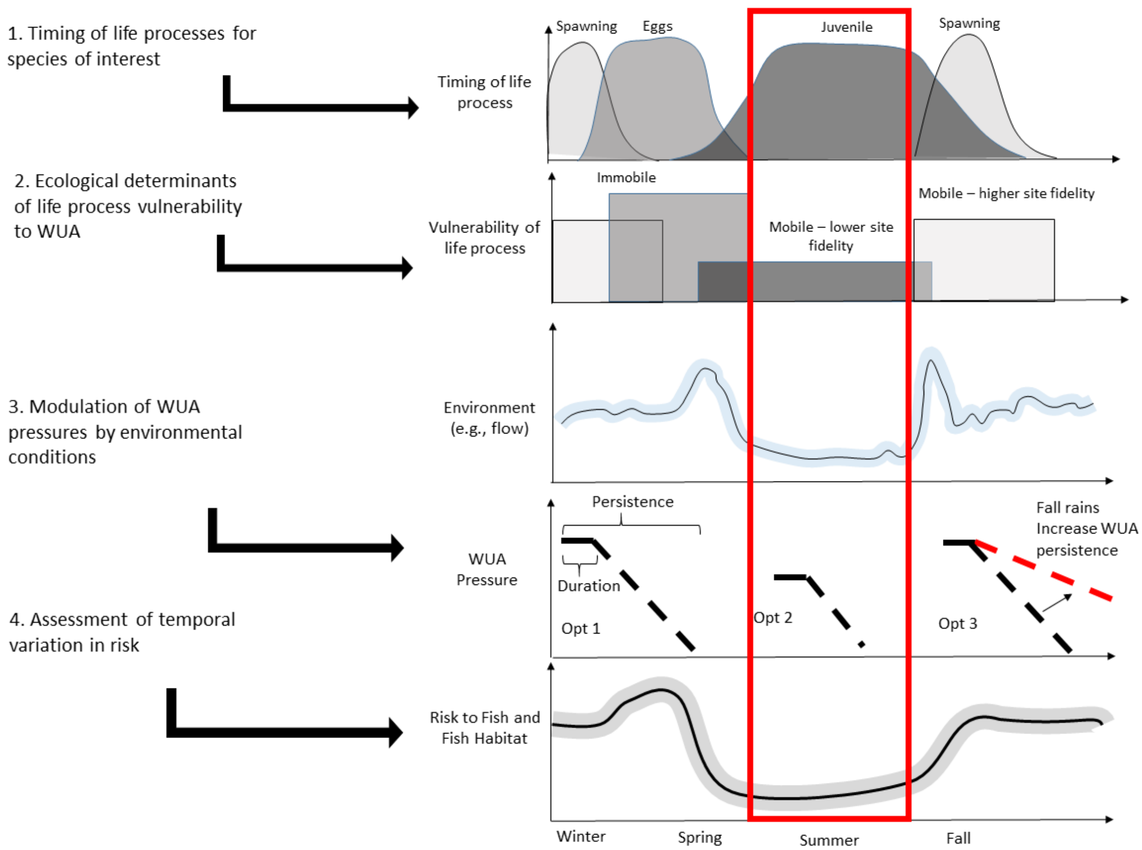

Figure 8. Conceptual model of the key components to guide the development, modification, and application of timing windows. The primary aim of a timing window is to reduce the risk of a WUA to a population or ecosystem, thus the essential element for effective application is an approximation of how WUA risk varies through time. There are several key components to this, which are represented as different panels. First, fish complete different life processes (e.g., spawning, rearing, migration) at different times of the year. Each process occurs over a range of dates that can be thought of as overlapping distributions (top panel). Each of these stages will differ in its vulnerability to pressures (second panel); for instance, eggs are immobile and may be more strongly impacted by work relative to mobile juveniles or adults. The realized pressure experienced from a WUA can also be strongly modified by environmental and physical habitat conditions such as flow or precipitation, which vary over different time scales (third panel from top). As a result, the pressure during and after a WUA may differ considerably depending on timing. In this example, magnitude and temporal persistence of a WUA increases during higher flows in the fall, relative to lower flow periods in the summer (fourth panel). Collectively, these elements define the temporal trajectory of risk (bottom panel). Timing windows (red box) would ideally be developed and applied during periods that minimize risk, which could be considered cumulatively through time. Each level of information may have uncertainty, which will propagate uncertainty to the final estimate of risk through time (represented by grey shading around the line).

The conceptual model in Figure 8 is presented in the context of assessing a single WUA and species. However, in principle the approach could be layered to consider multiple WUAs (i.e., cumulative effects) as well as the risk of one or more WUAs to broader fish communities (see section 6.5.4). These extensions may be considerably more complex in practice; for instance, multiple WUAs may have cumulative effects on risk that are non-additive. It is also important to note that in many situations the risk to fish and fish habitat may not exhibit temporal variation, i.e., the bottom panel in Figure 8 would depict a flat line, or periods of lower risk may be too short or unpredictable for work to occur. In these cases, timing windows will not be effective and other mitigation measures will be necessary.

Each component of this conceptual model requires different information about the focal species, habitat, and WUA, which collectively define an integrated measure of relative risk across the year. This in turn can inform the definition of the start and end of timing windows that minimize risk. While subsequent sections discuss these components in more detail, we summarize key points here as a set of broad questions, which could be used as preliminary criteria to guide timing window development, application, and modification.

Fish Life Processes

1. What are the species of interest?
2. Do they use the potentially affected habitat for a life process (if so, which process)?
3. Does the timing of their use overlap with works or WUA pressures?
4. Is the exposed life process likely to be negatively affected by the WUA pressures (i.e., is it vulnerable or sensitive to the WUA)?
5. Does the exposed life process have relatively higher vulnerability to the WUA than life processes at other times of year?
6. Do individuals aggregate during the life process such that there is a higher proportion of the population at risk of exposure to the pressure?
7. Are their known environmental drivers for this process that could help refine the start/end time of the process?

WUA Characteristics

1. Are WUA pressures transient or permanent?
2. Based on WUA pressure pathways, do the PoEs suggest timing will be effective?
3. What is the temporal scale of the WUA?
4. How do pressures vary through time after a WUA is completed?

Habitat Characteristics

1. Are there expected interactions between WUAs and habitat?
2. Is the habitat expected to change? If so, is the timing of change predictable or episodic?
3. What is the mechanism of habitat change?
4. Are there habitat-mediated delayed pressures?
5. Are there other local or regional pressures that might modify the WUA pressure?

A significant amount of information is required to address many of these questions, including the ecology and vulnerability of the focal species and affected habitat as well as the types of effects from the WUA. Some of this information, however, is available in existing reports or documents, with the PoE CSAS (Brownscombe and Smokorowski 2021) providing high-level guidance on likely pressures from WUAs. Similarly, summary information on species life history (Scott and Crossman 1998; Coker et al. 2001) or traits (Frimpon and Angermeier 2009) can help determine the likelihood of exposure and potential vulnerability of life processes. An example of how this type of species-specific information could be compiled to support the creation or modification of a timing window is presented in Table 2, with the end point determining the probability that a species will be exposed to a WUA pressure. Life processes determined to have a high probability of exposure to a WUA based on Table 2 should then be assessed for the vulnerability of the WUA of interest (or types of WUA likely to occur within that region). The combination of these two elements, exposure and vulnerability, can help identify lower risk time periods when works can occur.

Table 2. Summary of information that may be relevant to collect on fishes and their life processes to inform the creation or modification of timing windows and assess the potential risk of exposure for a life process to a WUA pressure. As a demonstration, the table is populated with information specific to Alewife (Alosa pseudoharengus) in the lower Laurentian Great Lakes (Lane et al. 1996; Scott and Crossman 1998; Eakins 2021). This table is a modified version of one created by Don Little from the Toronto and Region Conservation Authority and was used and expanded upon with permission.

Metrics of Interest		**Life Process**					
		Migration	**Spawning**	**Natal**	**Rearing**	**Feeding**	**Refuge**
General Time Period		April-May	June-August	July-August	August-November	September-May	-
Duration		-	4-6 weeks	3-7 days	-	-	-
System	*Lake*	√	√	√	√	√	-
	Stream	-	-	-	-	-	-
	Estuary	-	-	-	-	-	-
	Coastal (Marine)	-	-	-	-	-	-
Preferred Temp (°C)	*Min*	-	9	15.6	-	16	-
	Mean	-	13	-	-	-	-
	Max	-	21	22.2	-	21	-
Substrate Affinity	*Clay*	low	low	low	low	low	-
	Silt	low	low	low	low	low	-
	Sand	low	high	high	low	low	-
	Gravel	low	high	high	low	low	-
	Rubble	low	high	high	low	low	-
	Cobble	low	high	high	low	low	-
	Boulder	low	high	high	low	low	-
	Bedrock	low	high	high	low	low	-
	Other	-	-	-	-	-	-
	Submergent	low	low	low	low	low	-

Metrics of Interest		Life Process					
		Migration	Spawning	Natal	Rearing	Feeding	Refuge
Vegetation Affinity	*Emergent*	low	low	low	low	low	-
Preferred Depth(s) (m)	*0-1*	-	√	√	-	-	-
	"1-2"	-	√	√	√	-	
	"2-5"	-	√	-	√	-	-
	"5-10"	√	-	-	√	√	-
	10+	√	-	-	-	√	-
Environmental Influences of Life Process	*Temperature*	√	√	√	√	√	-
	Light	-	√	-	-	-	-
	Hydrology	-	-	-	-	-	-
	Meteorology	-	-	-	-	-	-
	Water Quality	-	-	-	-	-	-
	Food Availability	-	-	-	√	√	-
	Other	-	-	-	-	-	-
Additional Considerations	*Foraging Strategy*	-	-	-	Pelagic	Pelagic	-
	Food Source	-	-	-	Zooplankton	Zooplankton	-
	Mobility	-	-	Immobile	-	-	-
Likely Time of Day When Exposed to WUA	*All Day*	-	-	-	-	-	-
	Day	-	-	-	-	-	-
	Night	-	√	-	√	-	-
	Crepuscular	-	-	-	-	-	-
Behavioural Notes		-	Diel movements (offshore during day)	Immobile	Diel movements (offshore during day)	-	-
Probability (Exposure to WUA)		None	High	High	Low	None	Unk

5.1. FISH LIFE PROCESSES

Freshwater fishes exhibit highly diverse morphology, behaviour, and life history strategies (Scott and Crossman 1998; Mims et al. 2010). Diet and habitat requirements often vary within a species throughout their development (Werner and Gilliam 1984; Shuter 1990). Consequently, resource availability within a species' habitat must also vary to match the requirements of each life stage (Shuter 1990), since habitat for all-life stages are essential to the completion of species' life cycle (Minns et al. 1996). To limit impairments to a habitat's capacity to support life processes for fish, it is important to understand the variety of species that may utilize that habitat and the time periods they are likely to be most reliant on the habitat and thus more vulnerable to pressures.

Timing windows are primarily used to protect one of many species during time periods when an individual or the population may be particularly sensitive to the pressures associated with a WUA. Therefore, an understanding of life processes of fish is important when seeking to create or adjust a timing window. Here we briefly discuss the life processes of fish highlighted at the bottom of each of DFOs PoE diagrams, (Brownscombe and Smokorowski 2021) with particular emphasis on the suitability of timing windows for mitigating impacts from WUA pressures as well as a brief discussion of why fish may be vulnerable or sensitive during each process.

Despite the noted importance of all life processes for the persistence of a population, some characteristics of a life process may make them amenable to be used to inform a timing window. Specifically, timing windows will be easier to define and potentially more effective as a mitigation measure (i.e., suitable) when a life process:

- Has a defined start and end period (i.e., is discrete)
- Is known to occur at a specific time (e.g., over certain weeks or months)
- Is repeated on an annual basis
- Occurs within a specific habitat type or location
- Involves a substantial proportion of the population (or individuals are present in high densities)

Life processes will show variable levels of vulnerability to a WUA and its associated pressures. This vulnerability will be species-specific and depend on the timing of the process and its alignment with the timing of the WUA pressure. Life history components that dictate the vulnerability of a species or species' groups to a WUA pressure may include spawning strategy (e.g., pelagic/benthic or semelparous/iteroparous), foraging strategy (e.g., filter feeder, visual predator), size at maturity, specificity of habitat associations (i.e., narrow habitat niche), home range size and mobility, and their general position in the water column (e.g., benthic, pelagic; see Harvey et al. 2017). In general, however, life processes of species that occupy narrow habitat or foraging niches (i.e., specialists) are likely to be more vulnerable to WUA pressures than generalists since they will have fewer alternatives should their habitat or forage base be impacted negatively (Wilson et al. 2008). Similarly, life processes that cannot adapt or acclimate to changing habitat conditions (e.g., thermal regimes), would also be considered more vulnerable given limited capacity to cope with future stressors (Pankhurst and Munday 2011).

Compiling species-specific information on life process vulnerability can be challenging given the noted diversity of species in Canada as well as the variety of ecosystem conditions a single species may experience within their range. To address this challenge, several studies focus on life history traits rather than species-specific assessments, with studies identifying traits that may increase species vulnerability to environmental changes such as temperature (e.g., thermal tolerance; Dahlke et al. 2020; Nyboer et al. 2021), traits that may increase risk of extirpation or extinction (e.g., body size, age at maturation; Olden et al. 2008; van der Lee and Koops 2016), or reproductive traits that are linked to the stability of the ecosystem (Winemiller 2005). Such an approach has the advantage of providing a mechanistic link between a species' traits and environmental drivers (McGill et al. 2006), which in turn can inform predictions on how a species (or species' that share a trait) may respond to a perturbation.

An important caveat to many of these works, however, is that they are often focused more on permanent changes in either aquatic ecosystems or vital rates, and such pressures are beyond what a timing window would be expected to mitigate. Additional work is therefore required to understand impacts on life processes from short-term WUA pressures, and a trait-based approach holds promise since data are available that define species' life history traits (see Frimpon and Angermeier 2009) as well as life stage-specific habitat requirements (e.g., Coker et al. 2001). When combined, this information can help determine traits of species that are likely to be affected, their potential vulnerability if exposed to a pressure, and the likelihood that they will occupy the affected habitat. More specific information on potential vulnerabilities for the six life processes identified in DFOs PoE framework is presented in the section below.

5.1.1. Migration

Suitability: Migration is linked to other life processes including feeding, spawning, or seeking refugia, with definitions also emphasizing the need for movement by a majority of the population between two habitats over a distance larger than a species' typical home range with some fixed periodicity (see Lucas and Baras 2008). Based on this definition, timing windows hold promise for providing protection during this life process provided the period of migration and the movement corridors can be defined.

Vulnerability: There are two primary means whereby migration may be interrupted, the first will prevent passage along a migration corridor (i.e., physio-chemical barrier) and the second will impact an individual such that they cannot complete the migration (i.e., reduction in fitness). While physical barriers to migration can clearly block access to necessary habitats or force populations to aggregate in sub-optimal habitat, conditions above or below barriers may also preclude an individual's ability to migrate. For example, areas downstream of barriers can have variable oxygen concentrations and water temperatures, if fish avoid these areas or if they incur an oxygen debt that reduces their ability to successfully bypass a structure, migration failure may occur (see Lucas and Baras 2008). During migration, individuals may be sensitive to WUA pressures, particularly if their energy reserves are low and/or migration distances are extensive (e.g., elevated temperatures in Sockeye Salmon; Crossin et al. 2008). In these situations, an individual's response to the WUA pressure and their ability to successfully complete their migration will depend on their initial fitness or condition (Lucas and Baras 2008). Regardless of the mechanism, migration failure will have a carry-over effect related to the endpoint life process e.g., failure to reach spawning habitat and thus failure to spawn or failure during downstream migration and thus failure to reach suitable rearing habitat). As such, the reason for a migration is critical in determining the risk to the individual or population from interruptions to this life process. Table 3 summarizes some of the drivers and predictors of migration both for individuals and at the population level.

Key Considerations:

- Reason for migration
- Duration of migration
- Extent or distance of migration

- Portion of population involved in migration
- Movement path
- Mobility of the species
- Condition of individuals undertaking the migration

5.1.2. Spawning

Suitability: As detailed in Section 5, spawning is the life process most frequently used to define timing windows in Canada. Most species spawn annually, within a defined and limited time period, and in a specific habitat (or suite of habitat conditions). This can mean that a high proportion of the adult population will be in these locations at the same time and thus more vulnerable to a WUA pressure. Spawning is also well-studied, and the drivers/cues of spawning and spawning migration are well documented for many species (Scott and Crossman 1998; Table 3). The availability of this type of information makes modifying timing windows around spawning periods tenable relative to some other life processes.

Vulnerability: Disturbances during spawning can reduce the reproductive output of the population. Fish display a wide variety of spawning strategies and behaviours and utilize diverse spawning habitats. Species may exhibit semelparous (reproduce only once in their lifetime) or iteroparous (reproduce multiple times) spawning strategies, which may dictate the magnitude of the effect of a WUA. Spawning failure for a semelparous species may have greater population-level consequences since once resources are invested for spawning, an individual cannot readily re-allocate these resources should local habitat conditions be unsuitable. In contrast, while in the short-term spawning may be similarly affected for iteroparous species, they can potentially delay spawning until conditions improve. The vulnerability of a spawning strategy will also be influenced by other life history traits of the species or population, including age at maturity, proportion of population spawning, and fecundity (Velez-Espino et al. 2006), thus, a holistic understanding of a species' spawning strategy is required to full assess their vulnerability.

Regardless of strategy, for fishes that aggregate during spawning, increased density within a confined spawning area may expose a larger portion of the population to WUA pressures than would typically be found in one area, a situation that may temporarily elevate risk associated with WUAs taking place at the same time (i.e., increased chance for mass mortality events). Any disturbance that elicits a stress response in an individual can impact behaviour and potentially reproductive output, although the specific response will be dependent on the timing and magnitude of the stress response (Schreck 2010). Short-term disturbances may induce escape behaviour that can create oxygen deficiency in an individual that will need to be resolved (i.e., individuals will need to rest and recover) before spawning can resume (van Overzee and Rijnsdorp 2015). A WUA pressure that delays the release or fertilization of eggs can lead to overripening of eggs wherein their quality and fertilization rates will decrease (Springate et al. 1984); if prolonged, such a delay may lead to a missed spawning opportunity (Rideout et al. 2000). For mating behaviour, WUA pressures may interrupt routines typically performed before or during a spawning event (e.g., increased turbidity can alter mate selection; Glotzbecker et al. 2015). Since spawning-related behavioural routines vary among species, Rowe and Hutchings (2003) suggest that the complexity of the behaviour may dictate the extent of the disturbance from a WUA pressure. Finally, spawning adults and embryos may also be more susceptible to some forms of disturbance than other life stages since these life stages have the narrowest thermal tolerance and lowest aerobic capacity, making them the most sensitive to temperature changes related to a WUA pressure (Dahlke et al. 2020).

Key Considerations:

- Spawning strategy (e.g., semelparous vs iteroparous)
- Duration of spawning period
- Spawning habitat requirements (e.g., physical habitat, depth, flow)
- Densities of individuals during spawning
- Behaviour during spawning (e.g., nest building, courtship)

5.1.3. Natal

Suitability: As the product of spawning, the natal life process will occur immediately afterwards and, to an extent, some part of natal life will occur within timing windows that are appropriately defined for spawning. This is primarily true for spring-spawning fishes, as growth and development of eggs may happen rapidly (e.g., Walleye within 12-18 days; Scott and Crossman 1998), which increases the suitability of timing windows for protecting this life process. Application of timing windows to protect natal life processes for fall spawning species may be more challenging given the protracted nature of egg development (i.e., can occur throughout the winter with emergence sometimes as late as spring).

Vulnerability: Like spawning, disturbances during the natal period will reduce the reproductive output of the population. Egg development is influenced by environmental conditions, notably temperature (Pauly and Pullin 1988) and survival of eggs is often naturally low (Houde 2009), with considerable variability depending as well on habitat conditions (e.g., substrate composition at the spawning site; Marsden et al. 1995) or water temperature (Ivan et al. 2010; Gagliano et al. 2007). WUA pressures that will alter environmental conditions during egg development may increase natal mortality either directly (i.e., lethal temperature shift or smothering by sediment) or indirectly (i.e., reduced growth rates leading to increased mortality both during the natal and rearing life processes). The former would be examples of what Houde (1989) described as episodic mortality, wherein a brief WUA pressure results in a short-term high-mortality event. In contrast, more indirect impacts are aligned with more subtle changes in daily rates of mortality or slight reductions in growth rates (Houde 1989). Both types of early life stage mortality can significantly affect recruitment, but while subtle changes are more common (Houde 1989), WUA pressures that cause episodic events are more noticeable and therefore likely to be documented.

Key Considerations:

- Timing of spawning for a given species
- Duration of egg development
- Variability in development rates based on environmental conditions (e.g., temperature)
- Vulnerability of eggs to WUA/Pressures

5.1.4. Rearing

Suitability: For rearing, the potential utility of timing windows is dependent on a species' life history. For species with passive movement post larval emergence, density of individuals may decline during these early phases and association with specific habitat features may also be absent making timing windows less useful as a mitigation measure (e.g., Walleye; Sesterhenn et al. 2014). Similarly, active dispersal by juveniles is difficult to predict and reduces local density (Radinger and Wolter 2014). In contrast, for species that afford some care to their young by exhibiting nest guarding behaviour (e.g., Smallmouth Bass (*Micropterus dolomieu*)) or protection of young after swim-up (e.g., Bowfin (*Amia calva*)), young may be aggregated in discrete areas for an extended period, which would increase the utility of timing windows for limiting WUA/Pressures.

Vulnerability: Like natal processes, during the rearing phase fish are sensitive to perturbations in habitat conditions including changes in temperature, reductions in dissolved oxygen or protective cover and increases in sedimentation or turbidity. This period is dominated by high mortality and growth rates, both of which show considerable interannual variability. These metrics are also linked, with slower growth typically associated with increased mortality (Houde 1997). Any WUA pressure that will alter or slow growth rates during the larval-juvenile phases will therefore influence recruitment. This includes changes to the availability of suitable prey resources in sufficient concentrations since larval fish are gape-limited predators with high energetic demands (Houde and Zastrow 1993). Mismatches in the timing of larval emergence and the presence of suitable prey are a well-established hypothesis for early life-stage recruitment failure (in Houde 2009). Similarly, following yolk absorption, larval fish need to begin feeding before they are nutritionally deprived, at which point starvation cannot be prevented (even if feeding commences after this point). The duration of tolerance to this deprivation is dependent both on the size of larvae (shorter for smaller larvae; Miller et al. 1988 in Houde 2009) and the temperature (longer in cooler temperatures). Predation is a major source of mortality during the larval and juvenile phases and is typically size-selective, with survival therefore favouring larger and/or faster growing larvae (Houde 2009). As such, WUA pressures that may delay spawning, interfere with emergence of prey resources (typically phytoplankton, zooplankton, or other invertebrates), or reduce larval growth rates may have residual impacts on recruitment.

Reaching appropriate nursery habitat is critical to finding suitable prey and avoiding predation. Transport or retention of eggs and larvae in suitable or unsuitable nursery habitat is thus a driver of inter-annual variability in recruitment success (Cowan and Shaw 2002 – in Houde 2009). Early life stages have limited swimming capacities (Lucas and Baras 2008) and are therefore reliant on flow within rivers or currents in lakes to transport them to suitable nursery habitat. As they mature and become more mobile, even seemingly short-distance migrations (i.e., diel movements inshore and offshore) are important to survival and growth of fishes. This is particularly true for larval or juvenile fishes since they have limited energy reserves and must balance foraging needs with increased susceptibility to predation during movements away from nursery habitat (Lucas and Baras 2008). WUA pressures that may alter flow or current and consequently limit access to suitable nursery habitat may thus impact growth and survival of early life stages. Finally, for species that exhibit nest or brood guarding behaviour during rearing, a WUA pressure may alter adult behaviour such that the nest is abandoned temporarily, which may allow predators to enter the nest (Zuckerman and Suski 2013). Further, nest guarding species may aggregate in specific habitats (e.g., over 300 adult Largemouth Bass/ha in some instances (Weis and Sass 2011)); thus, a WUA pressure in that area may affect a larger portion of the population at one time.

Key Considerations:

- Mobility and dispersal extent of early-life phases of the species
- Density of individuals within a habitat
- Nest or brood guarding behaviour
- Vulnerability of growth to WUA pressure

- Vulnerability of prey items to WUA pressure

5.1.5. Feeding

Suitability: Due to the protracted nature of this life process, it is likely the most challenging to protect with timing windows. There can be considerable variation both among and within populations of the same species in terms of foraging strategy (e.g., there are three distinct patterns of habitat use and activity within a population of Northern Pike; Kobler et al. 2009), which increases the challenge of providing more general protection to a species or population with timing windows. Similarly, while some species will forage year-round, others may have periods of greater foraging activity followed by periods of relative inactivity (e.g., some Centrarchids during the winter; Suski and Ridgway 2009). An additional challenge is that fish may adjust their foraging habitat throughout their life history or seasonally to better target resources while limiting risk (Shuter 1990).

Vulnerability: Periods of food deprivation, particularly if protracted, can alter the fitness of an individual and lead to physiological (e.g., impaired immune function, oxidative stress; Pascual et al. 2003; Caruso et al. 2011) or behavioural (e.g., malaise, delayed migration; Wang et al. 2006; Midwood et al. 2016) changes. However, given the prevalence of periods of limited food availability in natural systems, fishes have a variety of adaptive responses that can help maximize survival (Wang et al. 2006; McCue 2010). For example, in the short-term, a fish may increase activity in search of food, but if unsuccessful this may be followed by a shift to reduced activity and thus lower energy expenditure (Méndez and Wieser 1993). As such, the greatest risk to feeding from a WUA pressure will occur when it is protracted and prevents fish from successfully foraging (e.g., increases in turbidity can limit foraging success in visual predators; Hecht and van der Lingen 1992). For some species, there are periods when foraging is particularly important for future life processes, notably for some spring spawning fishes like Northern Pike and Walleye that continue to forage throughout the winter to support egg development (Zhao et al. 2008; Harvey 2009). Disruptions during these time periods may thus have carryover effects and reduce spawning success. Finally, a WUA pressure may influence the food supply for a species such that, while their behaviour or ability to look for food are not directly affected, the availability of forage material may be reduced.

Key Considerations:

- Primary prey item
- Influence of WUA pressure on forage base
- Foraging habitat
- Criticality of foraging time period (e.g., winter embryogenesis)
- Duration of period of food deprivation from WUA pressure

5.1.6. Refuge

Suitability: During certain times of year fishes may seek refuge in specific habitats when conditions elsewhere are less favourable. Examples include seasonal shifts in depth to target thermal optima (e.g., Lake Trout (*Salvelinus namaycush*) during summer; McMeans et al. 2020), avoidance of hypolimnetic oxygen deficits (e.g., Walleye in a eutrophic embayment; Brooks et al. 2022), finding more stable conditions in the winter (e.g., stream fishes moving to deeper, slower pools; Lucas and Baras 2008), and avoidance of predators (e.g., shift by prey fishes from lentic to lotic systems; He and Wright 1992). Timing windows have the potential to provide protection for fishes when refuge habitat is essential, particularly for species that exhibit annual refuge-seeking behaviour and utilize these habitats for a limited time period. As such, appropriate application of timing windows requires knowledge of the drivers behind the need for refuge as well as the timing of their use.

Vulnerability: By definition, the use of refuge implies that other formerly suitable habitat areas are unavailable. The amount of habitat available for refuge is an important consideration when evaluating risk since more limited refuge habitat may result in increased density and thus impacts from a WUA pressure may be experienced by a larger portion of the population. Additionally, the reason behind seeking a specific refuge and the conditions therein are relevant to ensure a WUA pressure does not shift habitat conditions within the refugia towards those being avoided in the formerly occupied habitat.

Key Considerations:

- Reason for seeking refuge
- Duration of refuge period
- Availability of refuge habitat
- Size of refuge habitat

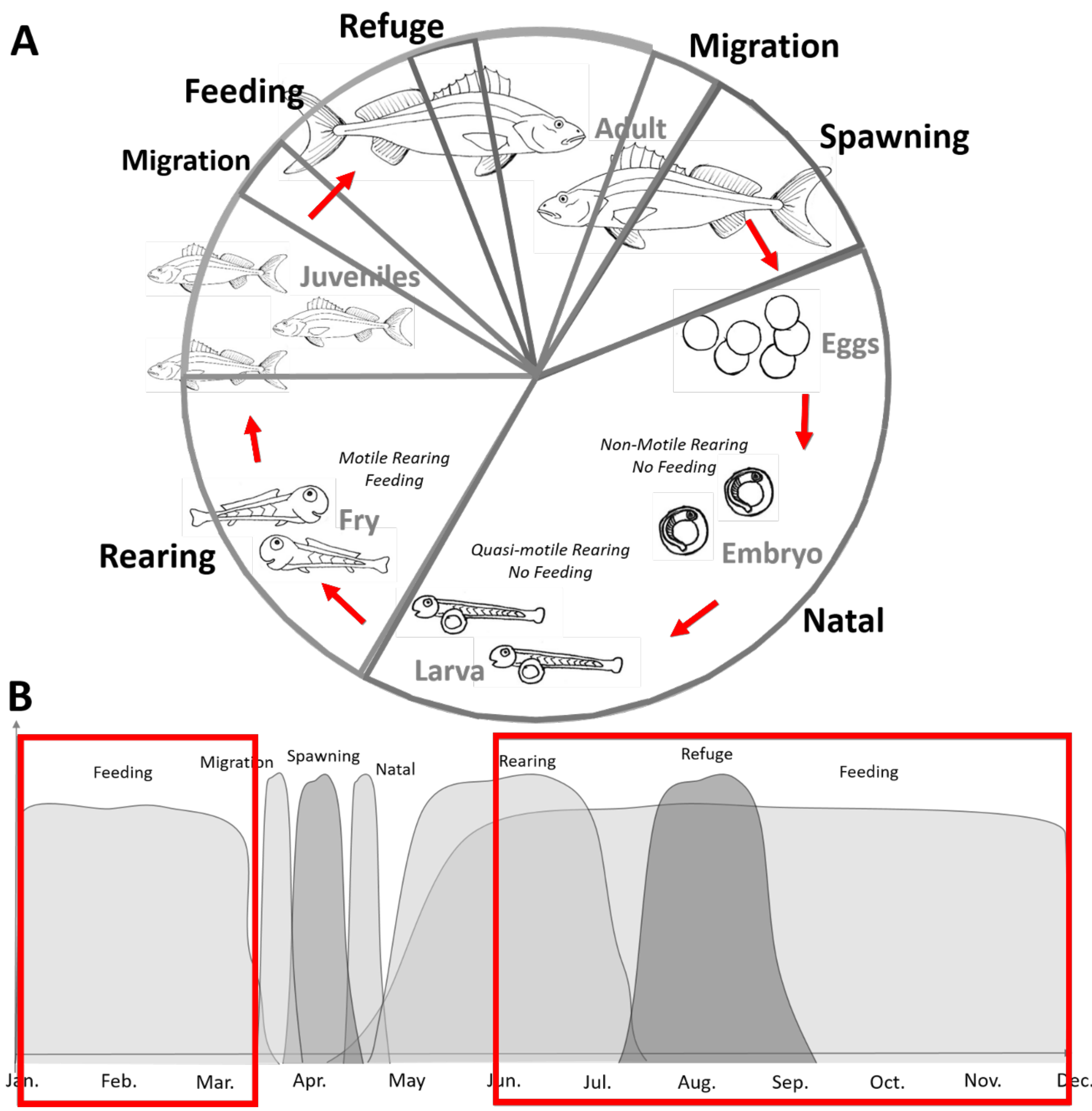

Figure 9. A) generalized timing of life processes for a fish species. B) Example of timing and duration of life processes for Walleye (Sander vitreus) in the lower Laurentian Great Lakes with the timing window (red box) showing the life processes that are not protected from WUA pressures.

5.2. ENVIRONMENTAL PREDICTORS OF TIMING IN FISH

The timing of life processes and the habitat requirements and conditions necessary for their completion vary among species and populations. Figure 9 shows a generalized annual cycle of life processes for a spring spawning freshwater species. These processes are intimately linked to environmental conditions, which may trigger the start of a process or set the pace for progression through the process (e.g., accelerated growth and development in eggs in warmer temperatures; Pauly and Pullin 1988). As such, variation in the start and duration of a process is to be expected among years within a population as well as spatially within a species.

Lucas and Baras (2008) provide an overview of factors influencing the start of migration for freshwater fishes and note that a combination of internal and external factors will dictate migration behaviour (summarized in Table 3). Similar linkages are likely present for other life processes. While more research is undoubtedly required to confirm proposed connections between these drivers and the resulting process, when information is available it can prove useful for defining or refining the application of timing windows to mitigate negative effects from WUA pressures on life processes.

More specifically, knowledge of the external or environmental drivers of life processes can help inform decisions on whether it is safe within that year to expand more generally defined timing windows (or work within restricted activity periods) without affecting life processes. For example, if water temperatures must reach a base threshold before a species will start to spawn and it has been colder than usual, it may be safe to extend the work window that year, at least until individuals of that species are detected near the spawning grounds.

Table 3. Summary of potential drivers of life processes (i.e., factors that may control the start or end of a life process). Interactions among these factors are likely and must be considered. Drivers are split into external and internal groupings to emphasize how an individual's internal state will also dictate when they begin a life process or transition between processes (adapted from Lucas and Baras 2008).

	Driver	**Migration**	**Spawning**	**Natal**	**Rearing**	**Feeding**	**Refuge**	**Specific Drivers of Life Processes**
External	*Temperature*	X	X	X	X	X	X	Increasing or decreasing temperatures, cumulative degree day
	Light	X	X	-	-	X	-	Diel, hours of light, intensity, influence on prey (e.g., phytoplankton), moon phase
	Hydrology	X	X	-	-	-	X	Rates of flow, flooding,
	Meteorology	X	-	-	-	-	X	Rainfall (influences hydrology), barometric pressure, ice cover
	Water Quality	X	-	-	-	X	X	Dissolved oxygen, contaminants, turbidity
	Food Availability	X	-	-	X	X	X	Prey density, prey size (gape-limiting), competition
Internal	*Genetic and ontogenetic factors*	X	X	X	X	X	-	Inherited life process traits (e.g., river vs lake spawning in walleye)
	Hunger and metabolic balance	X	X	X	-	X	X	Standard metabolic rate, temperature
	Homing	X	X	X	-	X	X	Natal origin
	Behaviour	X	X	-	-	X	X	Individually variable, linked to metabolic rate
	Predator avoidance	X	-	-	X	X	X	Density of predators

5.3. WUA CHARACTERISTICS

The effectiveness of timing windows as a mitigation measure depends on characteristics of WUAs and their associated pressure pathways and endpoints. While a comprehensive discussion of specific WUAs is beyond the scope of this document, this section focuses on broad WUA characteristics that are important to consider for the development, application, and modification of timing windows. Specifically, we discuss the timing and persistence of pressures as key determinants of the potential for timing windows to mitigate WUA impacts. In general, timing windows will be easier to define and potentially more effective as a mitigation measure when:

- WUA pressures are transient rather than permanent
- The trajectory of residual pressure after the WUA concludes can be defined and is predictable

5.3.1. Timing

The importance of timing will vary among pressures associated with a given WUA. PoE diagrams (Brownscombe and Smokorowski 2021) could provide a starting point to broadly identify obvious places where timing does or does not influence pressures pathways. In some cases, pressures are permanent, e.g., the addition of structures such as hydro dams that permanently reduce or eliminate fish passage, and timing windows will not be an effective mitigation measure. By contrast, other pressures may be transient; for instance, suspended sediment concentration may increase while machinery operates in water, then decline once the WUA concludes. In these latter situations, applying timing windows to alter the timing of pressures could significantly change impacts to fish and fish habitat. For some major projects that exceed a year in duration, timing windows could still be an effective mitigation measure if risk to fish and fish habitat varies through time.

Bradford et al. (2015) suggests the following five criteria to assess the temporal scale of WUAs, which are useful to broadly identify categories of temporal scale. (1) Is the alteration permanent vs. reversible or transient? (2) Is the pressure highly frequent and should be considered cumulatively vs. a single event? (3) Is the duration shorter than a life stage of fish in the affected area? (4) Is the timing coincident with sensitive fish life processes? And (5) Is the duration sufficient to cause meaningful impact beyond what fish would experience from natural variation? Even with limited information, applying these criteria to pressures associated with a given WUA (identified from PoE diagrams) can give a preliminary approximation of where timing windows might be effectively applied as mitigation measures.

5.3.2. Persistence

While the course-scale assessments of PoE diagrams described above can identify where timing windows might (or might not) be effective, further information is needed to assess the magnitude of their effectiveness and the risks of working outside of them. Assessing the risk of a WUA typically involves consideration of the potential magnitude, spatial extent, and temporal persistence of pressures and impacts (Bradford et al. 2015). Persistence is particularly relevant for timing windows and is defined as the time needed for any pressure to disappear, starting with the time a WUA begins to change a habitat component, to the time that pressure is no longer present. The persistence of a WUA can be further broken into the *duration*, the pressure during the WUA, and the *continuing pressure* that persists after the WUA concludes (Figure 10). This distinction is important because the magnitude of pressure can vary through time and the shape of that trajectory should bear strongly on the development of timing windows and the risk of working outside of them. For example, extending work beyond a timing window where the continuing pressure rapidly declines (line 1 in Figure 10) would incur significantly less additional risk relative to a residual pressure that declines more gradually (line 2 in Figure 10). WUAs that cause continuing pressures over more extended periods (e.g., lines 3 or 4 in Figure 10) may require additional mitigation measures.

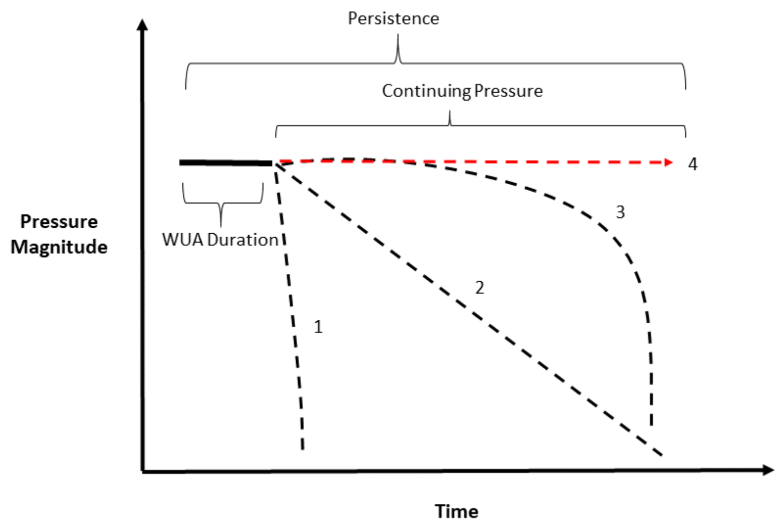

Figure 10. Schematic of the different components of persistence of pressure resulting from a WUA. WUA duration (solid line) defines the pressure experienced during the WUA, e.g., the impacts on sediment while machinery is working in water. The continuing pressure (dashed lines) describes how that pressure persists through time after the WUA concludes. There are many possible trajectories for these continuing pressures; some are represented by dashed lines 1-4. The red line (4) represents a situation where a WUA permanently impacts the ability of a habitat to support fish, thus timing windows would not be an effective mitigation measure. On the other end of the spectrum, line 1 represents a pressure that is immediately removed after a WUA concludes (e.g., underwater noise). Lines 2-3 represent intermediate cases where a pressure continues after the WUA, but gradually declines over time (e.g., suspended sediment concentration). There are various mechanisms influencing the shape of these curves. For example, point source pressures such as sediment or contaminants may be gradually diluted over time, or alternatively pressures may be actively reduced through restoration measures like vegetation planting.

There has been significant work on the persistence of some pressures in aquatic ecosystems, particularly those related to sediment and contaminants. For example, there are numerous studies focused on measuring and modelling particle fate and transport that could in principle be used to predict temporal scale and residual pressure trajectories (e.g., Johnson et al. 2000a; Johnson et al. 2000b; Lindim et al. 2016, Courtice and Naser 2020). However, there may be limited information to parameterize these tools in many situations and there is not a comprehensive heuristic framework to predict the magnitude and shape of persistence trajectories across WUAs. In addition, the persistence of WUAs can be strongly mediated by local habitat and environmental conditions, which can create complex residual pressure trajectories. This is further discussed in the Habitat Characteristics section (6.4).

5.4. HABITAT CHARACTERISTICS

5.4.1. Timing of Habitat Events and Interactions with WUAs

Effective timing windows should avoid overlapping with the timing of physical and ecological properties that form and maintain habitat. They should also ideally avoid conditions that may increase the magnitude and persistence of the WUA pressure. This section provides an overview of the primary physical and biological processes that structure aquatic habitats and how they might interact with WUAs (Table 4). The extraordinary variation in habitat conditions across Canada prohibit the discussion of all the possible interactions between habitat conditions and the characteristics of WUAs that increase pressure on aquatic habitats. Instead, this section aims to describe general concepts, along with illustrative examples, related to how the timing of habitat events or dynamics may interact to modulate WUA pressures. In general, timing windows will be easier to define and potentially more effective as a mitigation measure when:

- Habitat conditions are predictable
- The mechanisms of how habitat conditions mediate WUA pressures are understood

Table 4. Primary physical processes that shape aquatic habitats, change in habitat, and the potential interaction with WUAs that would lead to increased habitat vulnerability. Bolded habitat pressures indicate direct changes and regular text indicates indirect changes.

Process	Metric	System	Change in Habitat	Increase in Vulnerability to a WUA
Hydrological Regime	High flow	Streams and rivers	**Increase water quantity**, increase erosion, increase velocity.	Change in habitat quantity (i.e., wetted area and or structure and cover), increase suspended sediment.t.
Hydrological Regime	Low flow	Streams and rivers	**Decrease in base flow**, **decrease water quantity**, increase temperature.	Change or loss of habitat quantity (i.e., wetted area and or structure and cover), physical habitat quantity and quality, lethal and sublethal effects on fish from temperature pressures.
Hydrological Regime	Water levels	Lakes, wetlands, estuaries,	**Increase or decrease in water quantity.**	Change in habitat quantity (i.e., wetted area), physical habitat quantity and quality (i.e., flooded aquatic vegetation), change in exposure to wind/wave energy or ice scour
Ice Regime	Ice cover and formation	Streams, rivers, lakes, wetlands	**Decrease water quantity.**	Loss of habitat quantity (i.e., wetted area and or structure and cover) and quality (i.e., frazil ice).
Temperature Regime	Maximum temperature, exceedance of temperature thresholds (if known for species)	Streams and rivers, wetland, estuaries	**Decrease baseflow, decrease shade,** increase temperature.	Lethal and sublethal effects on fish from temperature.
Sediment Regime	Suspended sediment concentration	Streams and rivers	**Resuspension or entrainment of sediment.**	Increased suspended sediment, and sedimentation of fish habitat, loss of physical structure and cover.

Process	Metric	System	Change in Habitat	Increase in Vulnerability to a WUA
Water Chemistry	Dissolved oxygen concentration	Wetlands, estuaries, lakes	**Decrease dissolved oxygen.**	Direct change to physical habitat quantity and quality, lethal and sublethal effects on fish from low dissolved oxygen.
Nutrient Regime	Nutrient concentration	Streams, rivers, wetlands, estuaries, lakes	**Increase nutrients,** decrease dissolved oxygen.	Lethal and sublethal effects on fish from low dissolved oxygen.
Vegetation Regime	Biomass	Wetlands, streams, lakes	**Change in vegetation,** change in dissolved oxygen.	Loss of structure and cover, lethal and sublethal effects on fish from low dissolved oxygen.

Fish habitats are dynamic components of aquatic ecosystems and set the conditions fish experience. Examples of these dynamics include seasonal changes in snow dominated watersheds from winter low flows to high flows during spring freshet, which are then followed by low flows in summer, tidal cycles that result in changes in water levels and habitat conditions in near-shore marine habitats, and dramatic diurnal changes in water temperature and dissolved oxygen levels in wetlands. There are also more episodic habitat changes such as responses to weather events that can lead to less predictable habitat dynamics. These include large precipitation events that increase flows and water levels, cold snaps that lead to the formation of surface and anchor ice, and warm spells such as the recently experienced heat domes in western Canada that dramatically warm aquatic systems from the near-shore tidal habitats to headwater streams. These examples illustrate some of the range and scales in the timing of habitat change.

Temporal variation in habitat conditions contributes to creating and shaping the habitat itself, as well as the fish populations that inhabit them. For example, high stream flows can transport different components of the system downstream, delivering sediment and large wood that provide the foundation for habitat (Wohl 2019). This temporal variation in habitat conditions also directly influences fish and their life processes. Changes in habitat conditions that alter the quantity or quality of habitat can lead to density dependent and/or density independent impacts on growth, survival, and reproduction in fish. For example, density dependent effects on growth and mortality are often observed because of summer low flows or the generation of anchor ice in winter, which limit the amount of habitat available to fish in streams (Brown et al. 2010; Rosenfeld 2017). Episodic fall rains can also lead to density-independent mortality via scouring of egg mats or nests (Lapointe et al. 2000). For many species, specific temporal changes in habitat conditions, often associated with a specific life stage, result in strong population regulation. These are commonly described as habitat or population bottlenecks and can make populations more vulnerable to additional change. Therefore, the overlap in timing of habitat changes and fish life stage or process is particularly important for assessing risk to populations from additional habitat change that WUA may introduce to the system.

The degree of overlap and strength of the interaction between habitat conditions and WUAs will determine the magnitude and persistence of pressure a WUA exerts on fish and fish habitat. Changing habitat conditions can modulate the magnitude and persistence of WUA pressures on fish and fish habitat. For example, high flows may increase sediment erosion as flows in streams rise and erode destabilized stream banks. For WUAs with pressure pathways that lead to increase sediment loads via increase bank erosion (e.g., machines working within the wetted area) or in-channel sediment disturbance (e.g., gravel extraction), periods of high flows may increase the magnitude and persistence of high sediment concentrations. Therefore, structuring timing windows to reduce the overlap between habitat conditions that could increase the WUA pressure may mitigate the WUA pressures, however this requires information on cyclical patterns in the timing and magnitude of key habitat changes.

5.4.2. Predictability of Temporal Habitat Change

The use of timing windows might be most effective when the change in habitat conditions is predictable and strongly interacts with the WUA. The timing of key changes or shifts in habitat conditions are shaped by physical processes (e.g., hydrological process, tidal cycles, sediment transport, ice formation, water chemistry, and nutrient dynamics) that often follow predictable seasonal and/or diurnal patterns (Table 4). In some cases, the timing of habitat change is highly predictable, such as the change in near-shore water levels from tides. In contrast, changes in stream flows due to high precipitation storm events tend to be episodic and are much less predictable in space and time. Examining how predictable the timing of annual changes to habitat, as well as how these events might interact with the different pressures of a WUA will help determine the relative risk of a WUA and help select an effective timing window for instream works.

Predictability may differ for a given metric within a year as different mechanisms may drive seasonal changes in habitat. Consider the previous example where high flows increase WUA pressure by increasing suspended sediment concentrations. In many regions, high flows are produced by snow melt during freshet and storms that bring high precipitation. The timing and magnitude of snowmelt driven flows is reasonably predictable, with each system having its own hydrological regime. In contrast, high flows due to storm events may be less predictable in magnitude and timing as they depend on local weather patterns. The mechanisms that drive the delivery of water in these two cases are different and this means the effectiveness of a timing window put in place to avoid the high flows from storm events may be much more uncertain than one put in place to avoid high flows associated with annual freshet.

The predictability of habitat changes may vary dramatically across spatial and temporal scales. Continuing with the example of high flows in streams and rivers, where fall rains are common (e.g., coastal British Columbia) there is a high likelihood that large precipitation events will result in high flows during the fall months. However, unlike spring freshet the probability of high flows on a given day is much lower as it is driven more by local weather than regional climate. Furthermore, temporal autocorrelation contributes to the timing of spring freshet flows, whereby seasonal increases in air temperature drive increases in snow melt and run-off, while high flows due to fall rains tend to be decoupled and are typically multiple episodic high flow events. The temporal scale at which timing is considered will influence how predictable habitat change is, for instance, considering fall hydrology at larger temporal scales (i.e., on the order of weeks to months) decreases the uncertainty in predicting high flows.

5.4.3. Mechanisms of WUA Pressure and Changing Habitat Conditions

Considering the physical process that might interact with WUAs is important for assessing the risk. When WUAs interact with natural physical and biological processes it is important to consider the mechanism driving both the WUA pressure and the natural process. Lenzi and Marchi (2000) show how high flows due to fall rains may increase the risk of higher and more variable sediment loads compared to spring freshet. This is because the delivery of water and sediment downstream during a large precipitation event on bare soil is different than snow melt during freshet. They also show that sediment concentrations are higher and more variable for a given discharge during rain flood events compared to spring freshet due to differences in the delivery of water and sediment sources (Figure 11). During freshet the soil disturbed from freeze-thaw events is the main source of sediment whereas rainfall induced floods may generate sediment from localized landslides and channel bank erosion during high flows. This example illustrates how the same change in habitat (i.e., flow levels and suspended sediment) driven by different processes may affect the predictability of timing and potential risk associated with a WUA.

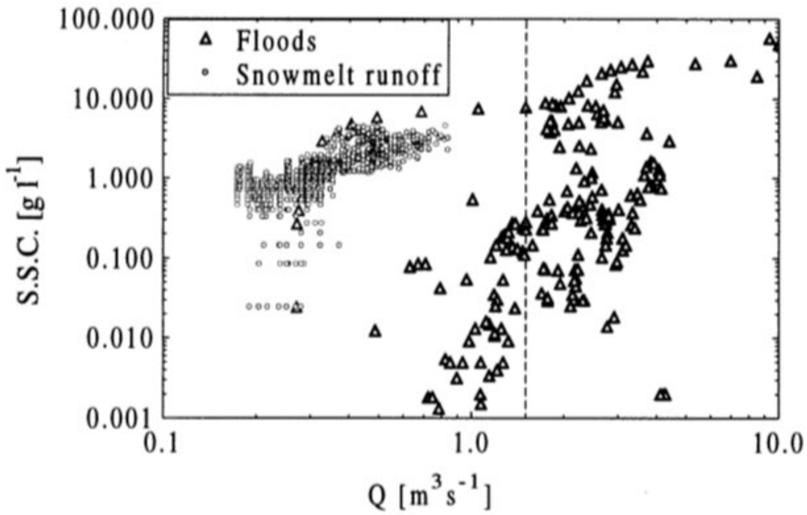

Figure 11. Taken from Lanzi and Marchi (2000) - Scatterplot of suspended sediment concentration (S.S.C.) vs. discharge for rainfall-induced floods and snowmelt runoff May–June 1990. The dashed line represents the threshold discharge above which bedload transport occurs.

5.4.4. Mismatch Between Habitat Change and Fish Vulnerability

Timing windows can be developed to minimize WUA impacts on habitat and/or fish life processes. However, the timing of habitat change can differ from the timing of vulnerability for fish. As described earlier, habitat change may be greatest when transitioning from one season to another or within a season when episodic weather conditions lead to dramatic habitat responses, e.g., storm events that reshape structural habitat morphology. Fish vulnerability may be decoupled from these transitional or episodic habitat events and may occur when habitat conditions are relatively stable. For example, habitat conditions may rapidly change during high flow events due to erosion, and the transport of sediment and large wood. However, for intact systems, there may still be good water quality conditions and ample refugia from high water velocities while these physical changes or shifts in habitat are taking place. In contrast, relatively stable summer low flows or water levels that coincide with peak water temperatures can create stressful conditions for fish by increasing density and physiological stress (see Section 6.4.1). These examples highlight the importance of considering the potential trade-off between the timing of habitat change and fish vulnerability and how they influence the effectiveness of a timing window.

5.4.5. Delayed Interactions Between WUA and Habitat Conditions

The original concepts and terminology that described the elements of WUA timing are presented in Figure 10, which shows the residual pressure as continuous, declining after the WUA was completed. This is a simplistic description of residual pressures and in some instances, they may be more complex. WUA pressures can manifest beyond the duration and residual pressure of a WUA, leading to impacts that not only extend the WUA persistence but are decoupled from the original WUA duration and residual pressure (Figure 12). Figure 12 shows a delayed residual pressure that is temporally disconnected from the pressures associated with the WUA duration and the residual pressure that immediately follows it. Delayed residual pressures are especially problematic if they extend outside the original timing window, diminishing the protections it provides to fish and fish habitat.

Delayed residual pressures can occur through multiple pathways. They are particularly likely when a WUA has altered the capacity of a habitat to withstand rapid environmental change such as a storm or high flow event. For example, instream construction conducted during the winter months when flows are low may decrease bank stability and erosion, but there would be minimal residual pressure during these low flow periods. However, significant residual pressure from the transport of the disturbed sediment and erosion of less stable banks may occur as flows exceed mobilization thresholds during the spring freshet melt. Thus, the residual pressure may occur months after the WUA was completed.

Continuing the previous example, increased sediment loads during freshet could decrease water clarity, which may prevent vegetation establishment and thus impact phytophillic species (Figure 13). Reduced vegetation cover in aquatic systems could have direct impacts on juvenile fish that use them as nursery sites as well as spawning later in the summer (Smokorowski and Pratt 2006) (i.e., the life process most timing windows are designed to protect). While not all WUA pressures will result in impacts on fish and fish habitat, the complexity and number of potential pathways for WUAs to interact with the variation in habitat conditions makes it difficult to consider all risks. A comprehensive consideration of how habitat changes and might interact with WUAs during and after construction would be a prudent exercise to capture many of the potential risks.

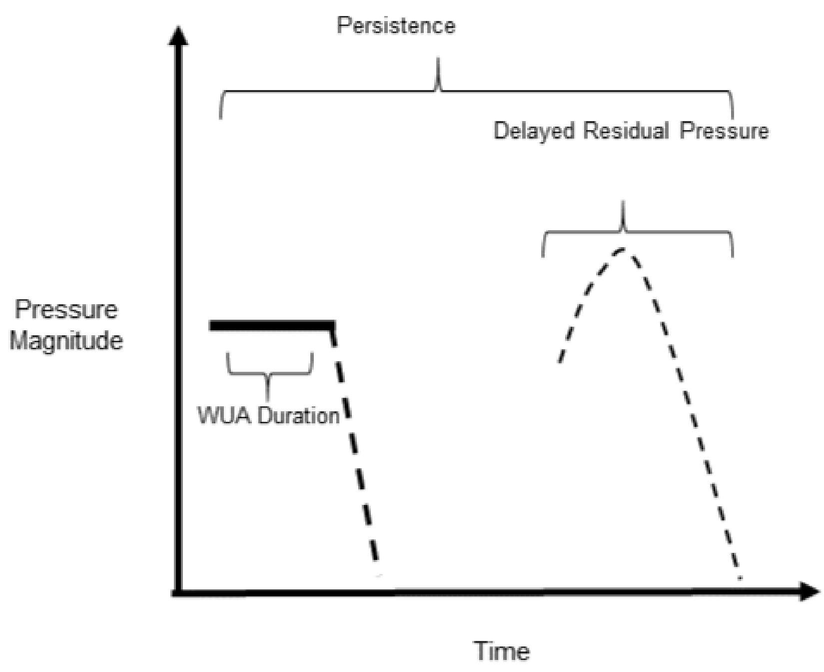

Figure 12. Temporal components describing a WUA's magnitude of impact during the work (WUA duration) and a delayed residual impact.

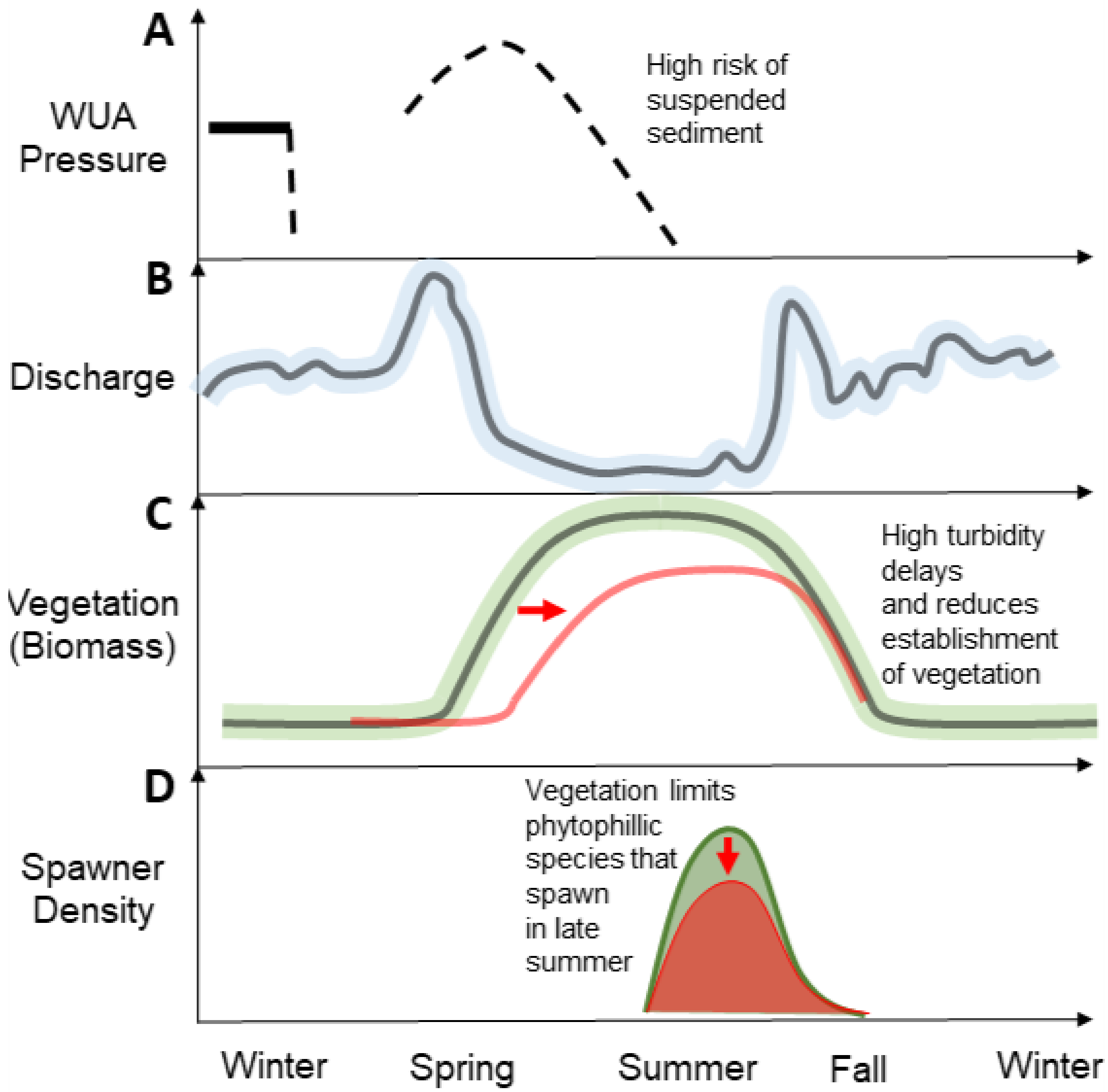

Figure 13. Hypothetical example of delayed residual pressure from a WUA on the density of phytophilic spawning species. Panel A) shows the risk of the WUA pressure including the duration (solid line) and residual pressures (dashed lines). Note the second delayed residual pressure; B) shows the change in discharge, C) shows vegetation growth in biomass where the green line shows typical growth (i.e., in the absence of the WUA) and the red line shows vegetation growth where establishment of vegetation is reduced due to increase sedimentation; D) shows the distribution of spawners (spawner density) where the green distribution is the typical spawner density in the absence of the WUA and the red distribution shows the reduction in spawner density due to reduced vegetation growth.

Delayed pressures may be particularly difficult to predict because the environmental conditions that lead to the delayed effects are likely to be decoupled (i.e., conditions when winter work is conducted may not predict conditions during freshet). Additionally, these delayed impacts may be overlooked for smaller projects that only span brief time periods. If construction is completed within weeks or a few months there may be no personnel on site to observe, monitor or mitigate these delayed impacts. For projects where this is a concern, a precautionary approach might include exploring the WUA PoEs through the entire year so that any potential delayed effects can be identified and followed up with monitoring and or mitigation measures.

5.4.6. Other Local and Regional Pressures Can Interact with WUAs

Interactions between natural landscape alteration and WUAs may also be an important consideration when developing or altering timing windows. The legacy of other land use activities and disturbance may interact with WUAs conducted downstream or at adjacent locations (Table 5). For example, there is a large body of work that describes both the short- and long-term legacy of forest harvest impacts in aquatic systems. This work suggests that forest harvest impacts may persist for ~100 years (Coble et al. 2020; Reid et al. 2020), depending on the productivity of the system and the continuation of land use activities. Upstream land use that influences hydrological responses is most likely to interact with downstream WUAs given that an increase in flood magnitude and frequency will be observed throughout the watershed. Other responses to upstream land use such as increased erosion may not lead to marked changes in habitat downstream as the impact may diffuse as sediment is transported downstream (Courtice and Naser 2019).

Table 5. Example of other possible local and regional pressures that may lead to cumulative pressures with WUAs.

Pressure	Potential Habitat Responses and Cumulative Pressures	Predicted Change to Habitat Timing	Reference
Forest Harvest	Increased water temperature, increase flood magnitude and frequency, increased suspended sediment, decrease channel complexity.	Earlier timing of freshet floods and related conditions.	Cheng 1989; St-Hilaire 2016; Tschaplinski and Pike 2017; Gronsdahl et al. 2018
Agriculture	Increased temperature, increased nutrient concentration, increased suspended sediment, increase peak flows, lower low flows.	Earlier peak temperatures that persist longer.	Meehan 1991; Poff et al. 2006
Mining	Increased suspended sediment, various – dependent on mining activity.	Increased sediment associated with snow melt and rainfall in watersheds with placer mining.	Pentz and Kostaschuk 1999
Water Withdrawal	Reduced flows, increase water temperature.	Earlier peak temperatures that persist longer, reduced and variable flows – highly dependent on management.	Hatfield et al. 2003
Dams and Reservoirs	Irregular hydrograph, increase temperatures, decreased temperatures, change in nutrients, reduced sediment transport.	Dramatic changes to timing of peak and low flows – highly dependent on management.	Poff et al. 2006 ; Clarke et al. 2008
Fire	Increase temperature, increase flood magnitude and frequency, increase suspended sediment.	Earlier timing of freshet floods and related conditions – magnitude of change may depend on whether logs are salvaged.	Gresswell 1999; Isaak et al. 2010; Beakes et al. 2014; Martens et al. 2019
Forest Disease Defoliation	Increase temperature, increase flood magnitude and frequency, increase suspended sediment.	Earlier timing of freshet floods – magnitude of change may depend on whether logs are salvaged.	Cheng 1989; Wehner and Stednick 2017

5.5. ADDITIONAL CONSIDERATIONS

5.5.1. Timing Window Efficiency

The main goal of timing windows is to reduce the risk associated with WUAs by protecting the more vulnerable life processes and habitat of fish. While maximizing the protection that timing windows provide will maximize their effectiveness, it could lead to unreasonably small timing windows that prohibit work for extended periods. Protections that limit development but do not further conservation and protection objectives may be socially and politically unacceptable. Evaluating the effectiveness of timing windows therefore involves a trade-off between the goals of the *Fisheries Act* and societal and political expectations. Therefore, additional considerations of the trade-offs between protections and development could be useful when evaluating timing window effectiveness.

Timing window efficiency is a concept that could inform effectiveness evaluations, and explicitly capture the trade-offs between protections and development. For example, consider a timing window that is developed to reduce the risk of a WUA pressure that increases in-stream temperatures and may physiologically stress fish. This could be the result of water extraction from a section of a river. The timing window being considered is composed of two periods before and after peak temperatures are typically observed (Figure 14). While peak temperatures always fall within a 40-day window, for the 20 years of historical data they have only been observed to occur within a 20-day period. The timing windows in Figure 14 (top panel) and 14 (bottom panel) appear to maximize protection of fish from peak temperatures but the longer timing window in Figure 14 (top panel) allows for more construction days and could be viewed as more efficient. Reducing timing windows more than required to meet the objective (e.g., to protect a given life process) may have diminishing returns in effectiveness. By contrast, timing windows that do not meet their objective (e.g., timing window overlaps with vulnerable life process), protection may be insufficient. Figure 14 (mid panel) shows a timing window that overlaps with the time of elevated risk.

Another important consideration is the appropriate temporal scale to characterize risk components such as life processes and habitat conditions. For example, developing a timing window based on habitat changes characterized at too coarse a temporal scale may lead to an inefficient timing window where most of the days are at low risk of interacting with a WUA, e.g., a timing window avoids all work in the fall months. In contrast, characterization at too fine a scale would result in a timing window that is too short and would require continual updating timing window (e.g., a timing window for one day at a time).

Timing window efficiency provides important context for when timing windows may be longer or shorter than required to meet the objective of the timing window. It requires knowledge about the effectiveness of a timing window with respect to risk reduction, which could be approximated based on the considerations outlined in this section. Considering efficiency is complicated by uncertainty in the calculation of risk and the effectiveness; however, uncertainty and variability could be considered in principle. Additional consideration of acceptable risk tolerance would also be necessary in any application but is not discussed here.

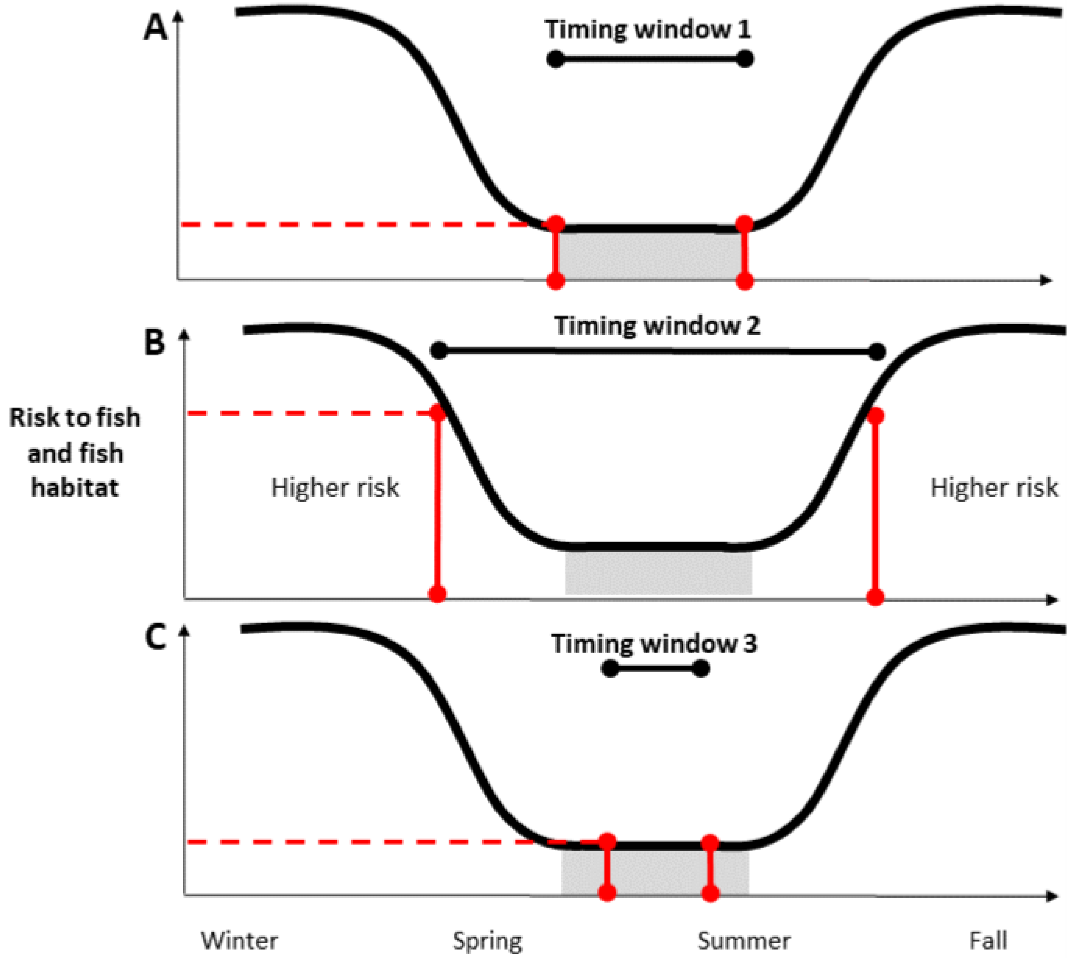

Figure 14. Schematic describing timing window efficiency concept. The risk of a particular WUA to fish and fish habitat is presented by the continuous black line. Days at risk from the WUA are represented by the black horizontal bar which is determined by the extent of the timing window (when work is allowed). The red vertical bars indicate the boundaries of the timing window and the horizontal dashed red lines indicate the maximum level of risk associated with the timing window. The grey shaded box represents the start and end of the period of lowest risk, and the area outside of this box is the expected period when risk is elevated (i.e., temperatures are above the thermal tolerance). Panel A shows a timing window that is precautionary as the days at risk determined by the timing window (when construction is allowed) is limited to the edge of the known low risk period (grey shaded area) Panel B shows a timing window that is less precautionary than the previous example as indicated by the wider horizontal black bar and longer construction period that occurs beyond the boundary of the low risk period (grey shaded box). Finally, panel C shows a timing window that is more precautionary than both previous examples as indicated by the timing window (area between the two vertical red bars) and being well within the low the risk period (grey shaded area). These panels show different levels of the trade-off between protection and development.

5.5.2. Timing Variability and Resilience

The predictability and consistency of fish life processes and habitat conditions underlie the development of timing windows and strongly influence their effectiveness. However, it is important to emphasize the intrinsic variability in the timing of ecological events, including life processes like migration and spawning as well as habitat forming processes like high flows and ice formation. This variability manifests at multiple spatial and temporal scales and is, in itself, an important dimension of ecological resilience, and in turn risk. The portfolio effect concept (Schindler et al. 2010) predicts that risk should be reduced with increasing diversity within populations; for example, variability in spawning timing can buffer populations against extreme events (Moore et al. 2010). This aligns with similar theory developed for whole ecosystem resilience and stability (Holling 1973; McMeans et al. 2016).

The idea that temporal variability underlies population and ecosystem resilience is relevant to timing windows for two reasons. First, attributes that contribute to timing window development can also provide insight into resilience. For example, highly synchronized life processes in some populations but not others may indicate reduced resilience (Moore et al. 2010) and thus greater risk. Second, timing windows may themselves influence the temporal variability of life processes, and therefore resilience, if they allow pressures to persist into the possible range of variability of a life process (Figure 15). In these instances, timing windows may protect a significant portion of a life process, but still reduce the potential temporal diversity of that process, and therefore the capacity of a population to adapt to changing conditions. Temporal diversity and resilience are therefore important for considering timing window risk and efficiency. This may be particularly important in situations where timing windows are applied over broad regions.

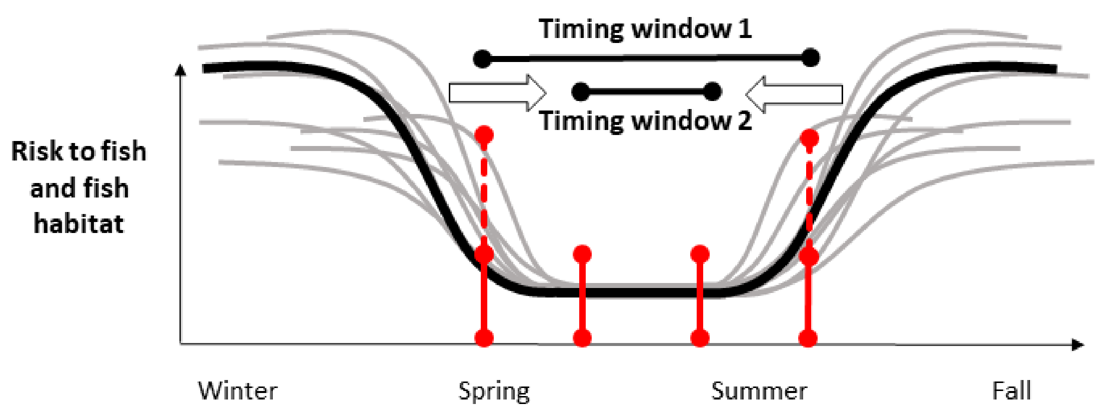

Figure 15. Similar to Figure 14, the timing of a life process or habitat may differ inter-annually as well as among individuals in a population. The lighter grey distributions indicate less common timing of life processes and different levels of risk of WUAs to fish and fish habitat, which could be due to abnormal abiotic conditions or higher frequencies of rare phenotypes within the population in some years. While extending the construction period (i.e., moving from timing window 1 to timing window 2) may not increase risk per se, it may reduce the diversity of possible timing, and thus impact the capacity of a population to respond to change, i.e., reduce its resilience.

While quantifying the nuances of resilience is not tractable in most management situations, timing windows should be continually re-assessed and refined to account for the temporal variability of key ecological processes. New information, which could be collected by proponents (e.g., Table 3), should feedback to modify timing windows as part of an adaptive management cycle (see Section 4.2.5.2.). Information about the variability of timing will also help to communicate the uncertainty of WUA risk and timing window efficiency (section 6.5.1 above).

5.5.3. Uncertainty and Precautionary Timing Windows

It is important to emphasize that data to inform the various components of risk discussed in this section (e.g., life process timing and vulnerability) will be limited in most situations. Consequently, there will be significant uncertainty in the risk of a WUA through time. Developing timing windows in the face of uncertainty should therefore consider the precautionary principle, and potentially err on the side of more cautious narrow timing windows when information to assess risk is poor and/or risk tolerance is low (e.g., for SARA listed species). As the quality of information increases, e.g., through monitoring (see section 7), timing windows could be modified to be broader, more efficient, and more tightly aligned with the processes they are made to protect. Uncertainty in the various components of risk is also relevant when considering authorizations of work outside timing windows. While most WUAs are completed inside the timing window prescribed in a *Fisheries Act* authorization, work can be authorized to extend outside a work window to accommodate changes to the timing of construction. The need to work beyond a timing window (or within a restricted activity period) could be due to construction delays or avoidance of unforeseen environmental conditions during the work window (e.g., large rain event prevented work) (Hatfield and Chilibeck 2008). Working beyond timing windows could compromise their protection and effectiveness. Thus, these authorizations warrant careful consideration of the additional risk that would be incurred. Greater uncertainty and reduced predictability in the life processes and habitat dynamics may require more precautionary expansions of timing windows and/or intensive monitoring to minimize impacts.

5.5.4. Community Considerations

Much of the use of timing windows focuses on reducing risk of harm to fish from an organism or population perspective. However, there are situations where the objective of a timing window is to protect multiple fish species or a fish community. Timing windows that are based on many species with similar timing of vulnerable life processes (e.g., fall spawners) may be effective for community level mitigation of WUA pressures and yet, community risk from human pressure may depend on other attributes like key species responses, alteration of food web pathways, or the timing of specific interactions that inordinately affect a species assemblage.

For example, a keystone species has a disproportionally large effect on the abundance of other community members considering its own abundance (Paine 1980; Power et al. 1996). As such, including protection for the life processes of a keystone species may potentially provide a timing window greater protection to fish community abundance, then strictly focusing on the number of species protected (Branton and Richardson 2011). Similarly, other research indicates that not all species interactions are equal (Paine 1980; McCann 2012). The strength and positioning of specific linkages among species may determine how WUA pressures transfer through the community, and these are expected to be associated with functional properties of communities like productivity and resilience (McMeans et al. 2016).

Determining the effectiveness of community-based timing windows is challenging. The timing aspect of fish community ecology is in an early stage of development. Knowledge of local species interactions may often be low, and therefore the uncertainty around the outcomes of pressures on the fish community will be high. Where community knowledge is scarce, the protection of species with similarly timed life stages may be a reasonable option for community protection with a timing window. Nevertheless, if the objective of a timing window is to reduce community level risk, then information of community structure and function including interactions should be valuable to a timing window development process. Strategic use of community models may be useful in some instances to compare potential outcomes (e.g., Whitney et al. 2020).

5.5.5. Climate Change

Climate change is shifting the timing of environmental events and habitat forming processes such as ice off and on dates and high and low flows or water levels. This in turn is altering the timing of fish life processes such as spawning and migrations (Portner and Peck 2010, Crozier and Hutchings 2014), and ultimately the trajectory of risk to fish and fish habitat through time. Timing windows developed for past or present conditions may therefore have reduced effectiveness in the future. While some climate change effects are predictable to some extent (e.g., broad-scale directional trends in phenology), there is significant uncertainty with respect to how populations and ecosystems will respond (Reto-Walther et al. 2002, Srivastava et al. 2022). Further, climate change is increasing the frequency of extreme environmental events at both ends of the distribution, e.g., extreme floods and droughts, which may dramatically alter the chronology of risk. Practitioners should consider buffering timing windows against uncertainty related to climate change (section 6.5.3) as well as integrating climate change into periodic re-assessments of timing window effectiveness (see section 7.1) within an adaptive management cycle.

6. ADVICE ON THE DESIGN OF STUDIES TO EVALUATE EFFECTIVENESS OF TIMING WINDOWS

Our third objective is to provide advice on the design of studies to evaluate timing window effectiveness. Effective timing windows reduce risk of harm to fish and fish habitat from WUA related pressures by limiting an activity's timing to low-risk periods. Creation or modification of a timing window, along with the application of a window in a new location, are reasons to evaluate effectiveness. An unexpected observation of fish spawning activity in the vicinity of a project during a timing window may serve as a warning that a scientific evaluation of effectiveness may be required. No specific guidance on the design of effectiveness studies is provided in the timing windows literature that we reviewed for this document. A lack of research documents that evaluate effectiveness of timing windows further restricts our ability to synthesize advice from that literature, as well as highlights the need for studies that evaluate the effectiveness of timing windows.

The development, modification, and application of timing windows should be based on scientific evidence and producing such evidence requires the selection of an appropriate study type and design. There are several factors to consider when choosing a study design including: defining the purpose and objectives of the proposed work, reviewing the pros and cons of the study types and designs, and identifying complementary study systems and tools. General study design considerations have been discussed at length in previous CSAS documents including specific information on the intensity of monitoring (DFO 2012; Smokorowski et al. 2015; Braun et al. 2019; DFO 2019b). There are also book chapters (Garton et al. 2005; Guy and Brown 2007) that can be consulted, as such, general advice on study design is not presented here.

Provincial or territorial timing windows may be applied as is or modified, or a new timing window may be created. The objectives may differ from one timing window to another. While all timing windows share a broader common objective, to reduce the risk of harm to fish and fish habitat from WUA related pressures, the specific intent and objectives associated with a timing window can vary. For example, the objective for a timing window could be to reduce the probability of exposure of fish life processes to a pressure, while another may tolerate some exposure provided it does not result in harm to fish and fish habitat above a tolerable level (e.g., mortality or measurable population effect). Evaluating the effectiveness of a timing window therefore requires knowledge of the objectives and intent of the timing window in question. Ideally these would be defined *a priori*, since they will help guide the definition of the window; however, when this information is not explicitly available for established timing windows, specific objectives (e.g., prevent works from occurring while the focal species is spawning) can be defined *post-hoc* and then evaluated. The information needs required to evaluate timing window effectiveness will thus differ depending on the availability and type of objective.

A tiered approach to evaluating timing window effectiveness can provide structured guidance that can be adapted to meet the needs of a specific timing window. Previous science advice has recommended a tiered approach to assess mitigation, restoration, and offsetting activities. This tiered approach includes compliance monitoring, functional monitoring, and effectiveness monitoring programs (DFO 2019b). All projects should include compliance monitoring to determine whether works were executed as described in an authorization or letter of advice. For projects where the impact is small and/or the link between the surrogate measure and fish productivity is well understood, functional monitoring can be applied since it uses indicators or surrogate measures to assess whether the management measure is functioning as intended (e.g., has there been a change in quality or quantity of habitat). Finally, when a project may have a large impact or has high uncertainty, full scale effectiveness monitoring should be employed to determine whether specific ecological milestones have been met (e.g., change in fish productivity; Braun et al. 2019). This type of tiered approach ensures that the objectives and approach of a monitoring program align with the information needs and uncertainty associated with a project. A similar tiered approach could be applied to assessments of the effectiveness of timing windows since it can help account for the variation in timing windows applied as mitigation measures by DFO.

To guide some initial thinking on timing window evaluation, we first present a tiered approach for effectiveness research and monitoring. We describe how the different tiers can lead to distinct insights about the effectiveness of timing windows and we provide examples of the types of studies that are suited to each tier, ending with a worked example. We then discuss the potential value of a weight of evidence approach for creating and evaluating timing windows.

6.1. A TIERED APPROACH FOR STUDIES OF TIMING WINDOW EFFECTIVENESS

Here we present a three-tiered process for monitoring or research that can help identify the kind of information and study types needed to evaluate the effectiveness of timing windows (Figure 16). Foundational for all tiers is that the study undertaken is scientifically rigorous and well-designed such that results can be used with confidence to assess the effectiveness of the timing window. The tiers are defined by the intent or objective of the studies that may occur within each tier and relate to the likelihood of exposure to a WUA pressure and/or the consequences of that exposure. Tiers may be linked the objective or intent of the timing window.

> **Tier 1** (*probability of exposure*) – Determine if there is overlap between the timing window and a life process, environmental factor, habitat condition, or WUA pressure.
>
> **Tier 2** (*consequence of exposure on a process*) – Determine if exposure to a WUA pressure during the timing window results in fish mortality and/or impairment of the habitat's capacity to support life processes of fish..
>
> **Tier 3** (*consequence of exposure to the population*) – Determine if exposure of a life process or habitat function to a WUA pressure during the timing window has higher order consequences above the individual or site level.

More detailed explanations of each tier as well as the types of questions it can address, examples of studies that could be completed, and potential limitations or challenges with implementing such studies are presented below.

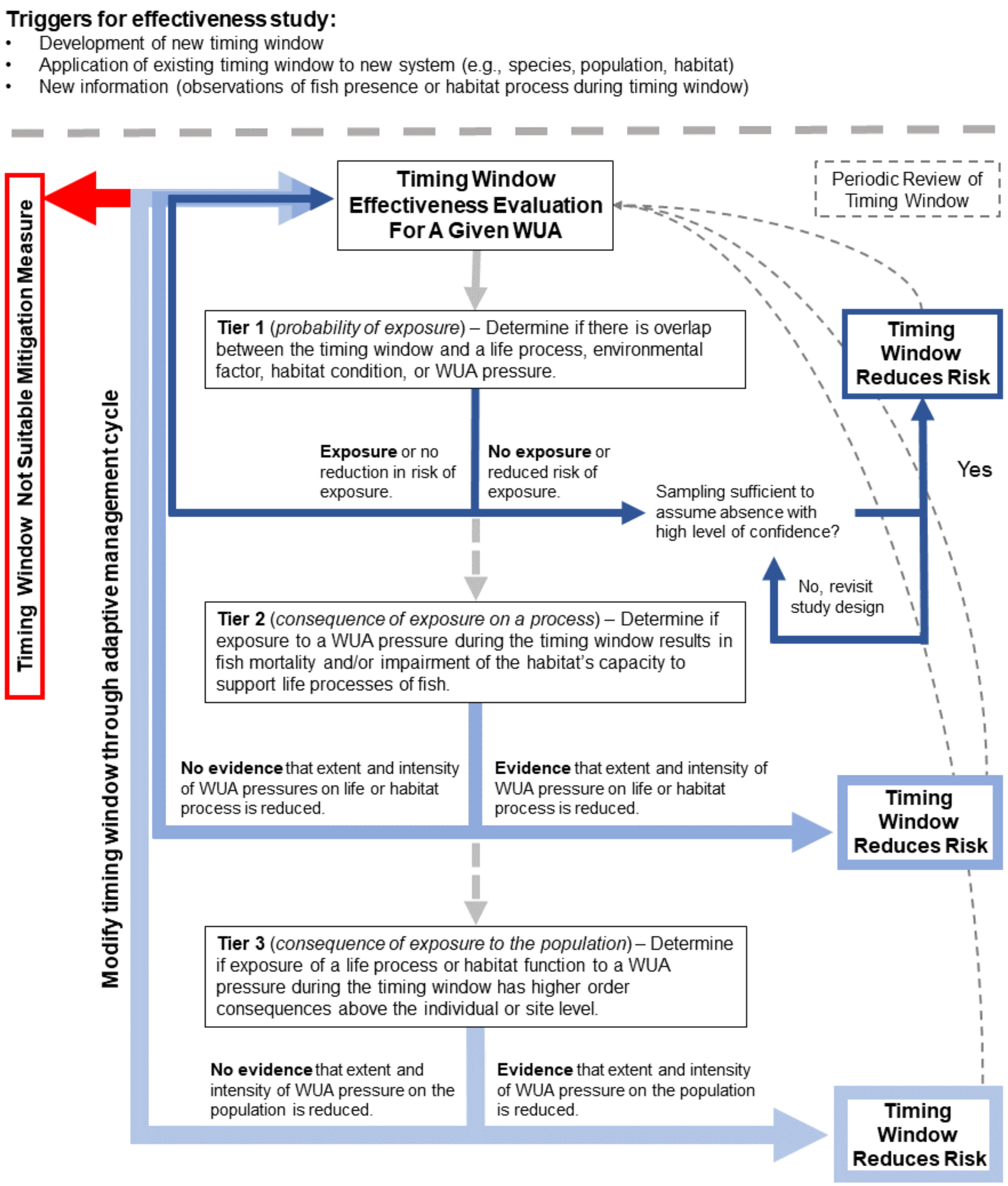

Figure 16. Conceptual diagram of a tiered approach to evaluating timing window effectiveness. Timing window effectiveness evaluations may be triggered by the development of new timing windows, new applications, or observations that the timing window may not be meeting its objective. Tiers of research/monitoring increase in the amount of inference drawn to evaluate timing window effectiveness as indicated by the increasing line width (thicker lines = more inference). Lower tiers may trigger the next more intensive (dashed grey lines) or tiers can be applied to questions of effectiveness independently. In all cases where there is evidence the timing window objectives are not being met, the timing window should be revisited or modified through an adaptive management process and in some cases it may be deemed that a timing window is not a suitable mitigation measure. Periodic evaluations of all timing windows could also be conducted to ensure climate related changes to species and habitats are considered (thin grey dashed line).

6.1.1. Tier 1 (probability of exposure)

The objective of this tier is to determine if the timing window overlaps with the fish life processes or the timing of key habitat processes it was intended to protect. Studies may confirm the presence of a species that is the target for protection of a timing window and may define the timing of a life process or habitat process if there is concern that there is overlap with an existing timing window. Similarly, a study may determine whether residual pressures from a WUA completed during the timing window persists into a period that is high-risk for fish and fish habitat. As an example, presence/absence data and occupancy models could be used to determine if the window was effective by confirming that focal species are not present or undertaking the target life process during the defined window. This kind of information could be obtained through a review of proponent monitoring documents or standard index monitoring, provided sampling was conducted for a sufficient duration and with suitable gear and intensity to ensure capture of focal species (if present). Information at this tier could inform the distribution and abundance of species used to inform timing windows and could inform the development of novel timing windows (or comparison of different options for timing windows) based on the observed timing and distribution of species or habitat processes.

Examples of Studies:

- Desktop exercise that reviews provincial or territorial databases of fish observations and habitat conditions (e.g., hydrology, temperature) to determine overlap between species observations (or habitat processes) and timing windows.
- Field studies that use standard fishing gear (e.g., electrofishing, minnow trapping, fyke nets), visual surveys (Weaver et al. 2014), electronic counters, or eDNA (Bylemans et al. 2016) to determine presence/absence of protected fish species during the timing window.
- Auto water samplers and/or turbidity loggers deployed to track suspended sediments in the water column during a period of increased water flow to determine whether there are residual effects from a WUA that extend outside of the timing window.
- Studies of fish migration behaviour, migration routes, and habitat use that use biotelemetry (e.g., acoustic telemetry, radio tracking, PIT tags) can show if and when tagged fish are present within potentially affected habitat (Larocque et al. 2020; Balazik et al. 2021).

6.1.2. Tier 2 (consequence of exposure on a process)

The objectives of Tier 2 are to link the exposure of the life process or habitat process to risk of harm from a WUA pressure. Studies at this tier may consider the duration, spatial extent, and intensity of WUA pressures and their effects (e.g., fish mortality) on fish life processes or habitat processes. Due to the complexity of making these linkages, an integrative research approach may be required. Field studies that track the response of a process to a specific WUA *in situ* would fit into this tier (Balazik et al. 2021), but lab-based studies that provide a more controlled assessment of the WUA pressure effect (Suedel et al. 2012) or models that can inform on the extent or duration of a WUA are also suitable for deriving estimates of risk (Courtice and Naser 2020). A key feature of this tier is the quantification of risk associated with the exposure of a life process or habitat process. Such a quantification is critical for contrasting risk for different processes occurring within in the yearly cycle (essential for comparing timing window options). Some of the challenges associated with this tier include: the transferability of findings from one system to another or lab to field, determining the spatial and temporal resolution required to capture the variability of a life process, and keeping knowledge up to date given the changing environment. These studies will provide information on whether exposure results in Fisheries

Act prohibitions under the current policy (i.e., death of fish and harmful alteration, disruption or destruction of fish habitat)

Examples of Studies:

- Fine-scale telemetry studies that can document changes in real-time to fish behaviour (Tsuda et al. 2006), energetics (e.g., use of accelerometer tags) (Wright et al. 2014), or habitat use (Chapman et al. 2019) in response to exposure to a WUA pressure.
- Field studies and models that can measure and predict the spatial extent, duration, or intensity of pressures (e.g., sediment) from a WUA within different windows and environmental conditions (e.g., quantitative fate-transport type models such as SSFATE (Johnson et al. 2000a; Johnson et al. 2000b).
- Bayesian belief networks (BBN) can be used in situations where local and regional data are limited. These models can incorporate expert knowledge and compare alternative options for management decisions. BBNs have been used to identify timing window effectiveness for dredging (Wu et al. 2017) and effectiveness of mitigation measures to reduce the pressures generated by different WUAs (Cormier et al. 2017).

6.1.3. Tier 3 (consequence of exposure to the population)

The objective of Tier 3 is to assess whether a timing window is reducing the risk of effects to the beyond the individual or site level (e.g. population or community). This tier may investigate how populations respond while a specific WUA takes place during a life process or habitat process that is targeted for protection. A large-scale field study may be the preferred method to evaluate effectiveness at this tier. This may take the form of an experiment where a WUA is manipulated, and the response is compared to a reference population. Applying this manipulation at times within the yearly cycle may provide insights into how the risk of population effect from a WUA varies with different timing windows. But this will be a challenging and specialized study to implement. Such population studies may not be tractable in many cases due to the confounding effects of seasonal change. A model simulation may prove to be valuable to provide information on population or community effects but requires sufficient information to parameterize such a model. For example, life stages in the model can be perturbed to identify when the vulnerability of the population may peak or identifying times of year where a WUA pressure may pose less risk.

Examples of Studies:

- Long term field studies that quantify population level responses to WUA pressures and contrast timing windows. These could be experiments (e.g., BACI designs) that explicitly manipulate timing windows, or observational studies that contrast timing windows in different systems. These types of studies face steep challenges such as transient dynamics, and limited ability to isolate the effects of timing windows from other mitigation measures. There is also an inherent conceptual challenge involved in measuring an effect that is being avoided. Consequently, Tier 3 investigations are less feasible to undertake empirically.
- Simulation models offer a more tractable avenue for Tier 3 studies. For species with sufficient information (e.g., salmonids), life cycle models or stage structured population models offer a means to evaluate timing window effectiveness at the population level. These approaches model the population-level outcomes of life stage-specific impacts (Nickelson and Lawson 1998; Jorgensen et al. 2021); thus, they can explicitly predict the population-level impacts of contrasting timing windows that protect various life processes. The utility of life cycle models may be reduced for species with more ecological limited information. In

these cases, less data-intensive modelling techniques (e.g., Bayesian Belief Networks, Joe Model) would be more appropriate. Semi-qualitative models can be useful to understand cumulative impacts of pressures on different endpoints, like a qualitative population response, during different timing windows (e.g., Joe Model) (DFO, 2019c).

- To explore community level vulnerability for data-rich situations ecosystem models could be parameterized, and mortality could be applied to species to determine which may have the largest impact on species of interest or the whole fish community (e.g., Ecopath-Ecosim; Christensen and Walters 2004).

7.1.4. Example Application of a Tiered Approach to Effectiveness

Here we describe an example of the general tiered approach to timing window effectiveness evaluation applied to salmonids. Protecting spawning for these species is a common objective for timing windows in Canada; 12 of 13 Provinces and Territories specifically mention this life process as a motivation for timing windows and are valued by human society. Spawning times are well defined for many salmonid populations and timing for this life process for many populations is generally consistent year to year. There is also significant evidence to suggest spawning is a particularly vulnerable life stage (e.g., Levine Fricke 2004).

Observations of spawning fish at a work site earlier or later than expected (i.e., inside the timing window) during compliance monitoring would trigger an investigation into timing window effectiveness. An investigator could apply the following tiered approach.

Tier 1: Initial investigations could focus on the extent of overlap of spawning in the timing window. There are numerous approaches that could be designed to detect the presence of spawners; these include visual surveys designed to detect spawning adults or redd surveys to detect the presence of eggs post spawning. Evidence of spawning within the timing window would indicate exposure to WUA pressures and that the timing window may not be effective. Estimates of detection probability would be important for determining absence of spawners (Bradford and Braun 2021).

Tier 2: To further examine timing window effectiveness, an investigator could conduct a study to determine the effect of a WUA pressure on spawning (or review existing studies from the literature). This could include field surveys to monitor spawning behaviour as well as document pre-spawn mortality events for semelparous species, which can be a strong indicator of deleterious impacts. It could also be complemented by lab-based studies on egg retention in the presence and absence of pressures, such as sediment or contaminants.

Tier 3: If the WUA pressure was found to impact spawning, additional steps would be necessary to quantify its impact at the population level. The magnitude of the impact of a WUA on spawning is not directly commensurate with its impact on the whole population due to numerous processes occurring across the broader life cycle (e.g., compensatory dynamics). Since life processes are well studied for many salmonids, it is possible to parameterize life cycle models to test how impacts on spawning manifest at the population level. For example, mortality or egg deposition could be adjusted in the model to reflect pressures on spawners. Pess and Jordan (2019) provide comprehensive guidance on the development and application of life cycle models in the context of habitat restoration, which could easily be extended to investigate WUA impacts and timing window effectiveness.

Information obtained at any tier can be used by practitioners to refine timing windows, to inform their creation, and to address requests for extension of work beyond designated timing windows.

6.2. WEIGHT OF EVIDENCE APPROACH

The proposed tiered approach to evaluating timing window effectiveness draws on multiple sources of information that carry different weights of evidence but collectively provide powerful insights into our understanding of a system. A weight of evidence approach lends itself to evaluations of multiple sources of information and lines of evidence for how a system responded to modification or mitigation using a systematic, transparent, and logical approach (Forbes and Calow 2002; Burkhardt-Holm and Scheurer 2007). While Tier 1 allows for the dichotomous evaluation of whether there is overlap between the timing window and the presence of a life history or habitat process, Tiers 2 and 3 are more complex and no single line of evidence or study will provide complete information to determine if a timing window has reduced the risk of a WUA pressure. For instance, determining the risks of exposure to a WUA pressure may use a combination of lab studies that directly test the impact of a stressor on a particular life process as well as field studies that determine behavioral responses to a stressor. While the lab study may indicate the consequences of exposure, fish may behave differently in the wild in ways that reduce the risk of exposure to a WUA, e.g., by temporarily using alternative habitats. While the development of a weight of evidence approach is beyond the scope of this document, Forbes and Calow (2002) provide specific guidance on how to develop an approach and Connors et al. (2014) provide an excellent example.

6.3. ADDITIONAL CONSIDERATIONS

Timing window effectiveness evaluation is not a simple one-time test. A tiered approach provides guidance for standardization of the approach but recognizes the need for some flexibility in study specifics. This flexibility also aligns with the Canadian timing window approach given diverse fish community assemblages and habitat conditions and the variety of WUA pressures that need to be considered. Standardization is also important since each province or territory defines and manages timing windows differently (i.e., spatial, temporal and biological scales) and with often distinct objectives. The tiers are not intended to be hierarchical but results at lower levels may prompt investigations at a higher tier. It is important to periodically revisit timing windows to provide feedback and ensure that timing windows are up to date (i.e., consistent with most recent science as well as current ecological conditions). The revisiting step provides the opportunity to adjust timing windows, to further reduce risk making them more effective, which is consistent with an adaptive management approach.

7. CONCLUSIONS

Timing windows are a commonly applied mitigation measure within DFO and the extent of variation among existing windows and the fish species, life processes, and habitats they are intended to protect reflects the diversity of fish and habitats that occur in Canadian waters. The FFHPP is seeking to develop a framework to aid in the creation, modification, and assessment of timing windows and the information presented in this report is intended to support discussions to help shape scientific advice in support of this framework. Key considerations for the creation or modification of a timing window include determining the species present and their phenology, assessing species or process vulnerability (both generally and for specific WUAs), and assessing the temporal variation in risk.

While we found limited explicit evidence of efficacy, the intent of timing windows is rooted in basic ecology and species phenology such that if a life or habitat process is known to be at risk from a WUA pressure, then removing the pressure for that process should mitigate the harm. While conceptually sound, additional evidence of effectiveness will better support the rationale for the use of timing windows as will information related to when processes occur, and which are most at risk to specific WUA pressures. Considerations related to the features of WUA pressures, such as their duration, persistence, and extent as well as life or habitat process vulnerabilities can support a risk-based application of timing windows by defining the temporal variation in risk. The conceptual model presented herein can be adapted to support the application or refinement of existing windows to meet the needs of FFHPP-regulated activities by incorporating regional information on species phenology and environmental processes. The conceptual model also incorporates environmental processes as a step in assessing risk, and changes to the environment (e.g., climate change) will influence the timing of these processes and in turn the timing of fish life processes. By developing and working through such a model, lower risk periods can be estimated based on novel environmental conditions, which can help define or update the bounds of a timing window. The tiered approach for assessing timing window effectiveness presented here can similarly feed into an adaptative management approach that will support improved application. With more information on the phenology of a species within a region (gathered via monitoring), the efficiency of a timing window can be improved to ensure it covers the most vulnerable life processes of a species, while not unduly limiting WUAs.

8. REFERENCES CITED

Arlinghaus, R., Tillner, R., and Bork, M. 2015. Explaining participation rates in recreational fishing across industrialised countries. Fish. Manag. Ecol. 22(1): 45-55. doi:10.1111/fme.12075.

Balazik, M.T., Altman, S., Reine, K.J., and Katzenmeyer, A.W. 2021. Atlantic sturgeon movements in relation to a cutterhead dredge in the James River, Virginia. DOER Technical Notes Collection. ERDC/TN DOER-R31. Vicksburg, MS: US Army Engineer Research and Development Center. 1-14 p.

Balazik, M., Barber, M., Altman, S., Reine, K., Katzenmeyer, A., Bunch, A., and Garman, G. 2020. Dredging activity and associated sound have negligible effects on adult Atlantic sturgeon migration to spawning habitat in a large coastal river. PloS one 15(3): e0230029. doi:10.1371/journal.pone.0230029/.

Barnucz, J., Mandrak, N.E., Bouvier, L.D., Gaspardy, R., Price, D.A. 2015. Impacts of dredging on fish species at risk in Lake St. Clair, Ontario. DFO Can. Sci. Advis. Sec. Res. Doc. 2015/018. v + 12 p.

Beakes, M.P., Moore, J.W., Hayes, S.A., and Sogard, S.M. 2014. Wildfire and the effects of shifting stream temperature on salmonids. Ecosphere 5(5): 1–14. doi:10.1890/ES13-00325.1.

Berry, W.J., Rubinstein, N.I., Hinchey, E.K., Klein-MacPhee, G., and Clarke, D.G. 2011. Assessment of dredging-induced sedimentation effects on winter flounder (*Pseudopleuronectes americanus*) hatching success: results of laboratory investigations. In Western Dredging Association Technical Conference and Texas A&M Dredging Seminar. 47-57 p.

Bradford, M.J., and Braun, D.C. 2021. Regional and local effects drive changes in spawning stream occupancy in a sockeye salmon metapopulation. Can. J. Fish. Aquat. Sci. 78(8): 1084–1095. doi:10.1139/cjfas-2020-0463.

Bradford, M.J, Koops, M.A, and Randall, R.G. 2015. Science advice on a decision framework for managing residual impacts to fish and fish habitat. DFO Can. Sci. Advis. Sec. Res. Doc. 2014/112. v + 31 p

Braun, D.C., Smokorowski, K.E., Bradford, M.J., and Glover, L. 2019. A review of functional monitoring methods to assess mitigation, restoration, and offsetting activities in Canada. DFO Can. Sci. Advis. Sec. Res. Doc. 2019/057. vii + 75 p.

Breau, C. 2013. Knowledge of fish physiology used to set water temperature thresholds for inseason closures of Atlantic salmon (*Salmo salar*) recreational fisheries. DFO Can. Sci. Advis. Sec. Res. Doc. 2012/163. iii + 24 p.

Brooks, J.L, Midwood, J.D., Smith, A., Cooke, S.J., Flood, B., Boston, C.M., Semecsen, P., Doka, S.E., and Wells, M.G. 2022. Internal seiches as drivers of fish depth use in lakes. Limnol. Oceanogr.

Brown, R.S., Hubert, W.A., and Daly, S.F. 2011. A Primer on winter, ice, and fish: what fisheries biologists should know about winter ice processes and stream-dwelling fish. Fisheries 36(1): 8–26. doi:10.1577/03632415.2011.10389052.

Brownscombe, J.W., Smokorowski, K.E. 2021. Review of Pathways of Effects (PoE) diagrams in support of FFHPP risk assessment. DFO Can. Sci. Advis. Sec. Res. Doc. 2021/079. iv + 55 p.

Branton, M. and Richardson, J.S. 2011. Assessing the value of the umbrella-species concept for conservation planning with meta-analysis. Conserv. Biol. 25(1): 9-20. doi:10.1111/j.1523-1739.2010.01606.x.

Burkhardt-Holm, P., and Scheurer, K. 2007. Application of the weight-of-evidence approach to assess the decline of brown trout (*Salmo trutta*) in Swiss rivers. Aquat. Sci. 69(1): 51–70. doi:10.1007/s00027-006-0841-6.

Burt, N. 2002. Environmental windows as emerging issue in Europe. 1-12 p.

Burt, N. and Hayes, D. 2004. Framework for research leading to improved assessment of dredge generated plumes. HR Wallingford Ltd (Great Britain). 22-34 p.

Bylemans, J., Furlan, E.M., Hardy, C.M., McGuffie, P., Lintermans, M., and Gleeson, D.M. 2016. An environmental DNA-based method for monitoring spawning activity: a case study using the endangered Macquarie perch (*Macquaria australasica*). Methods Ecol. Evol. 8: 646-655. doi:10.1111/2041-210X.12709.

Carpenter, S.R., Stanley, E.H., and Vander Zanden, M.J. 2011. State of the world's freshwater ecosystems: physical, chemical, and biological changes. Annu. Rev. Environ. Resour. 36: 75-99. doi:10.1146/annurev-environ-021810-094524.

Carter, W.R. 1986. An argument for retaining periods of non-dedging for the protection of oyster resources in upper Chesapeake Bay. Maryland Department of Natural Resources. Annapolis, MD. 5-10 p.

Caruso, G., Denaro, M.G., Caruso, R., Mancari, F., Genovese, L. and Maricchiolo, G. 2011. Response to short term starvation of growth, haematological, biochemical and non-specific immune parameters in European sea bass (*Dicentrarchus labrax*) and blackspot sea bream (*Pagellus bogaraveo*). Mar. Environ. Re. 72(1-2): 46-52. doi:10.1016/j.marenvres.2011.04.005.

Caskenette, A.L., Durhack, T.C., and Enders, E.C. 2020. Review of information to guide the identification of Critical Habitat in the riparian zone for listed freshwater fishes and mussels. DFO Can. Sci. Advis. Sec. Res. Doc. 2020/049. vii + 67 p.

Cheng, J.D. 1989. Streamflow changes after clear-cut logging of a pine beetle-infested watershed in southern British Columbia, Canada. Water Resour. Res. 25(3): 449–456. doi:10.1029/WR025i003p00449.

Chapman, E.D., Miller, E.A., Singer, G.P., Hearn, A.R., Thomas, M.J., Brostoff, W.N., LaCivita, P.E., and Klimley, A.P. 2019. Spatiotemporal occurrence of green sturgeon at dredging and placement sites in the San Francisco estuary. Environ. Bio. Fishes 102(1): 27-40. doi:10.1007/s10641-018-0837-9.

Christensen, V. and Walters, C.J. 2004. Ecopath with ecosim: methods, capabilities and limitations. Ecol. Modell. 172(2–4): 109–139. doi:10.1016/j.ecolmodel.2003.09.003.

Chuine, I. and Régnière, J. 2017. Process-based models of phenology for plants and animals. Annu. Rev. Ecol. Evol. Syst. 48: 159-182. doi:0.1146/annurev-ecolsys-110316-022706.

Clarke, D., Ault, J., French, D., and Johnson, B. 2003. Dredging operations and environmental research program: building tools for objective determination of environmental windows. In Dredging'02: Key Technologies for Global Prosperity. 1-13 p.

Coble, A.A., Barnard, H., Du, E., Johnson, S., Jones, J., Keppeler, E., Kwon, H., Link, T.E., Penaluna, B.E., Reiter, M., River, M., Puettmann, K., and Wagenbrenner, J. 2020. Long-term hydrological response to forest harvest during seasonal low flow: Potential implications for current forest practices. Sci. Total Environ. 730: 138926. Elsevier B.V. doi:10.1016/j.scitotenv.2020.138926.

Coker, G.A., Portt, C.B., and Minns, C.K. 2001. Morphological and ecological characteristics of Canadian freshwater fishes. Can. MS Rpt. Fish. Aquat. Sci. 2554: iv + 89p.

Connor, M., Hunt, J., and Werme, C. 2005. Potential impacts of dredging on pacific herring in San Francisco Bay. In Final Draft White Paper. Prepared for the US Army Corps of Engineers South Pacific Division and the Long-Term Management Strategy Science Assessment and Data Gaps Workgroup Herring Subcommittee. iii + 82 p.

Connors, B.M., Marmorek, D.R., Olson, E., Hall, A.W., de la Cueva Bueno, P., Bensen, A., Bryan, K., Perrin, C., Parkinson, E., Abraham, D., Alexander, C., Murray, C., Smith, R., Grieg, L., and Farrell, G. 2014. Independent review of potential impacts of run-of-river hydroprojects on salmonid species in British Columbia. xiv + 59 p + Appendix 1-8.

Cormier, R., Kelble, C.R., Anderson, M.R., Allen, J.I., Grehan, A., and Gregersen, O. 2017. Moving from ecosystem-based policy objectives to operational implementation of ecosystem-based management measures. ICES J. Mar. Sci. 74(1): 406-413. doi:10.1093/icesjms/fsw181.

Courtice, G., and Naser, G. 2020. In-stream construction-induced suspended sediment in riverine ecosystems. River Res. Appl. 36(3): 327–337. doi:10.1002/rra.3559.

Crossin, G.T., Hinch, S.G., Cooke, S.J., Welch, D.W., Patterson, D.A., Jones, S.R.M., Lotto, A.G., Leggatt, R.A., Mathes, M.T., Shrimpton, J.M., and Van Der Kraak, G. 2008. Exposure to high temperature influences the behaviour, physiology, and survival of sockeye salmon during spawning migration. Can. J. Zool. 86(2): 127-140. doi:10.1139/Z07-122.

Dahlke, F.T., Wohlrab, S., Butzin, M. and Pörtner, H.O. 2020. Thermal bottlenecks in the life cycle define climate vulnerability of fish. Science 369(6499): 65-70. doi:10.1126/science.aaz3658.

DFO. 2012. Assessing the effectiveness of fish habitat compensation activities in Canada: monitoring design and metrics. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2012/060.

DFO. 2015. A science-based approach to assessing the impact of human activities on ecosystem components and function. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2015/020.

DFO. 2019a. Fish and Fish Habitat Protection Program Policy Statement.

DFO. 2019b. Science advice on operational guidance on functional monitoring: Surrogate metrics of fish productivity to assess the effectiveness of mitigation and offsetting measures. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2019/042.

DFO. 2019c. Review of Alberta Environment and Parks Cumulative Effects Assessment Joe Model. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2019/045.

DFO. 2021. Science advice on revisiting Pathways of Effects (PoE) diagrams in support of FFHPP risk assessment. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2021/053.

Dickerson, D.N. and Nelson, D.A. 1988. Proceedings of the national workshop on the methods to minimize dredging impacts on the sea turtles. US Army Corps of Engineers Report. 1-90 p.

Dickerson, D., Reine, K., Nelson, D., and Dickerson Jr, C. 1995. Assessment of sea turtle abundance in six South Atlantic US Channels. Miscellaneous Paper EL-95-5. US Army Engineer Waterways Experiment Station, Vicksburg, MS. ix + 124 p.

Dickerson, D.D., Reine, K.J., and Clarke, D.G. 1998. Economic impacts of environmental windows associated with dredging operations. US Army Engineers Waterways Experiment Station Vickburg, MS. 1-18 p.

Dickerson, D., Wolters, M., Theriot, C., and Slay, C. 2004. Dredging impacts on sea turtles in the Southeastern USA: a historical review of protection. In Proceedings of World Dredging Congress XVII, Dredging in a Sensitive Environment. 1-13 p.

Eakins, R.J. 2021. Ontario freshwater fishes life history database. Version 5.11.

ECORP, Inc. 2009. Literature review: fish behavioural response to dredging and dredging material placement activities. Report. 1-69 p.

Forbes, V.E. and Calow, P. 2002. Applying weight-of-evidence in retrospective ecological risk assessment when quantitative data are limited. Hum. Ecol. Risk Assess. 8(7): 1625–1639. doi:10.1080/20028091057529.

Forrest, J. and Miller-Rushing, A.J. 2010. Toward a synthetic understanding of the role of phenology in ecology and evolution. Philos. Trans. R. Soc. B. 365(1555): 3101-3112. doi:10.1098/rstb.2010.0145.

Frimpong, E.A. and Angermeier, P.L. 2009. Fish traits: a database of ecological and life-history traits of freshwater fishes of the United States. Fisheries 34(10): 487-495. doi:10.1577/1548-8446-34.10.487.

Fraser, M.W., Short, J., Kendrick, G., McLean, D., Keesing, J., Byrne, M., Caley, M.J., Clarke, D., Davis, A.R., and Erftemeijer, P.L. 2017. Effects of dredging on critical ecological processes for marine invertebrates, seagrasses and macroalgae, and the potential for management with environmental windows using Western Australia as a case study. Ecol. Indic. 78: 229-242. doi:10.1016/j.ecolind.2017.03.026.

Gagliano, M., McCormick, M.I., and Meekan, M.G. 2007. Temperature-induced shifts in selective pressure at a critical developmental transition. Oecologia 152(2): 219-225. doi:10.1007/s00442-006-0647-1.

Garton, E.O., Ratti, J.T., and Giudice, J.H., 2005. Research and experimental design. Techniques for wildlife investigations and management. Sixth edition. The Wildlife Society, Bethesda, Maryland, USA. 43-71 p.

Glotzbecker, G.J., Ward, J.L., Walters, D.M., and Blum, M.J. 2015. Turbidity alters pre-mating social interactions between native and invasive stream fishes. Freshw. Biol. 60(9): 1784-1793. doi:10.1111/fwb.12610.

Gresswell, R.E. 1999. Fire and aquatic ecosystems in forested biomes of North America. Trans. Am. Fish. Soc. 128(2): 193–221. doi:10.1577/1548-8659(1999)128<0193:faaeif>2.0.co;2.

Griffin, F.J., Smith, E.H., Vines, C.A. and Cherr, G.N. 2008. Impacts of suspended sediments on fertilization, embryonic development, and early life stages of the Pacific Herring, Clupea pallasi. A report to the US Army Corps of Engineers and the long-term environmental strategy environmental science work group. 1-32 p + Appendix 1-4.

Griffin, F.J., Smith, E.H., Vines, C.A., and Cherr, G.N. 2009. Impacts of suspended sediments on fertilization, embryonic development, and early larval life stages of the Pacific herring, Clupea pallasi. Biol. Bull. 216(2): 175-187. doi:10.1086/BBLv216n2p175.

Griffin, F.J., DiMarco, T., Menard, K.L., Newman, J.A., Smith, E.H., Vines, C.A., and Cherr, G.N. 2012. Larval Pacific herring (*Clupea pallasi*) survival in suspended sediment. Estuaries Coasts 35(5): 1229-1236. doi:10.1007/s12237-012-9518-7.

Gronsdahl, S., Moore, R.D., Rosenfeld, J., McCleary, R., and Winkler, R. 2019. Effects of forestry on summertime low flows and physical fish habitat in snowmelt-dominant headwater catchments of the Pacific Northwest. Hydrol. Process. 33(25): 3152–3168. doi:10.1002/hyp.13580.

Guy, C.S. and Brown, M.L., 2007. Analysis and interpretation of freshwater fisheries data. American Fisheries Society.

Harvey, B. 2009. A biological synopsis of northern pike (*Esox lucius*). Can. Manuscr. Rep. Fish. Aquat. Sci. 2885: v + 31 p.

Harvey, E., Wenger, A., Saunders, B., Newman, S., Wilson, S., Travers, M., Browne, N., Rawson, C., Clarke, D., and Hobbs, J. 2017. Effects of dredging-related pressures on critical ecological processes for finfish: a review and possible management strategies. Report of WAMSI Dredging Science Node Theme 8 Report. vii + 38 p + Appendix 1-5.

Hatfield, T. and Chilibeck, B. 2008. Kitimat to Summit Lake natural gas pipeline looping project — conceptual compensation plan for fish habitat. iii + 26 p + Appendix A-C.

Hatfield, T., Lewis, A., Ohlson, D., and Bradford, M. 2003. Development of instream flow thresholds as guidelines for reviewing proposed water uses. vi + 88 p.

He, X. and Wright, R.A. 1992. An experimental study of piscivore–planktivore interactions: population and community responses to predation. Can. J. Fish. Aquat. Sci. 49(6): 1176-1183. doi:10.1139/f92-132.

Hecht, T. and Van der Lingen, C.D. 1992. Turbidity-induced changes in feeding strategies of fish in estuaries. Afr. Zool. 27(3): 95-107. doi:10520/AJA00445096_644.

Hodgson, E.E., Wilson, S.M., and Moore, J.W. 2020. Changing estuaries and impacts on juvenile salmon: A systematic review. Glob. Chang. Biol. 26(4): 1986-2001.

Holling, C.S. 1973. Resiliance and stability of ecological systems. Annu. Rev. Ecol. Syst. 4: 1–23. doi:10.1146/annurev.es.04.110173.000245.

Houde, E.D. 1989. Subtleties and episodes in the early life of fishes. J. Fish Biol. 35: 29-38. doi:10.1111/j.1095-8649.1989.tb03043.x.

Houde, E.D. 1997. Patterns and trends in larval-stage growth and mortality of teleost fish. J. Fish Biol. 51: 52-83.

Houde, E.D. 2009. Recruitment variability. In Fish reproductive biology: implications for assessment and management. Edited by Jakobsen, T., Fogarty, M., and Moksness, E. 91-171 p.

Houde, E.D. and Zastrow, C.E. 1993. Ecosystem-and taxon-specific dynamic and energetics properties of larval fish assemblages. Bull. Mar. Sci. 53(2): 290-335.

Isaak, D.J., Luce, C.H., Rieman, B.E., Nagel, D.E., Peterson, E.E., Horan, D.L., Parkes, S., and Chandler, G.L. 2010. Effects of climate change and wildfire on stream temperatures and salmonid thermal habitat in a mountain river network. Ecol. Appl. 20(5): 1350–1371. doi:10.1890/09-0822.1.

Ivan, L.N., Rutherford, E.S., Riseng, C. and Tyler, J.A. 2010. Density, production, and survival of walleye (Sander vitreus) eggs in the Muskegon River, Michigan. J. Great Lakes Res. 36(2): 328-337. doi:10.1016/j.jglr.2010.02.010.

Johnson, B.H., Andersen, E., Isaji, T., Teeter, A.M., and Clarke, D.G. 2000a. Description of the SSFATE numerical modeling system. DOER Technical Notes Collection. ERDC/TN DOER-E10. Vicksburg, MS: US Army Engineer Research and Development Center. 1-12 p.

Johnson, B.H., Andersen, E., Isaji, T., Teeter, A.M., and Clarke, D.G. 2000b. Demonstration of the SSFATE numerical modeling system. DOER Technical Notes Collection. ERDC/TN DOER-E12. Vicksburg, MS: US Army Engineer Research and Development Center. 1-21 p.

Jorgensen, J.C., Nicol, C., Fogel, C., and Beechie, T.J. 2021. Identifying the potential of anadromous salmonid habitat restoration with life cycle models. PLoS One 16: 1–22. doi:10.1371/journal.pone.0256792.

Kjelland, M.E., Woodley, C.M., Swannack, T.M., and Smith, D.L. 2015. A review of the potential effects of suspended sediment on fishes: potential dredging-related physiological, behavioral, and transgenerational implications. Environ. Syst. Decis. 35(3): 334-350. doi:10.1007/s10669-015-9557-2.

Kobler, A., Klefoth, T., Mehner, T., and Arlinghaus, R., 2009. Coexistence of behavioural types in an aquatic top predator: a response to resource limitation? Oecologia 161(4): 837-847. doi:10.1007/s00442-009-1415-9.

Lane, J.A., C.B. Portt and C.K. Minns. 1996. Spawning habitat characteristics of Great Lakes fishes. Can. MS Rep. Fish. Aquat. Sci. 2368: v + 48 p.

Lapointe, M., Eaton, B., Driscoll, S., and Latulippe, C. 2000. Modelling the probability of salmonid egg pocket scour due to floods. Can. J. Fish. Aquat. Sci. 57(6): 1120–1130. doi:10.1139/f00-033.

Larocque, S., Boston, C.M., Midwood, J.D. 2020. Seasonal daily depth use patterns of acoustically tagged freshwater fishes informs nearshore fish community sampling protocols. Can. Tech. Rep. Fish. Aquat. Sci. 3409: viii + 38 p.

LaSalle, M.W., Clarke, D.G., Homziak, J., Lunz, J.D., and Fredette, T.J. 1991. A framework for assessing the need for seasonal restrictions on dredging and disposal operations. Technical Report D-91-1. US Army Engineer Waterways Experiment Station Vicksburg, MS. ii + 74 p.

Lenzi, M.A. and Marchi, L. 2000. Suspended sediment load during floods in a small stream of the Dolomites (northeastern Italy). Catena 39(4): 267–282. doi:10.1016/S0341-8162(00)00079-5.

Levine Fricke 2004. Framework for assessment of potential effects of dredging on sensitive fish species in San Francisco Bay - Final report. vii + 131 p.

Lindim, C., van Gils, J., and Cousins, I.T. 2016. A large-scale model for simulating the fate & transport of organic contaminants in river basins. Chemosphere 144: 803–810. doi:10.1016/j.chemosphere.2015.09.051.

Lucas, M. and Baras, E., 2008. Migration of freshwater fishes. John Wiley & Sons.

Marsden, J.E., Perkins, D.L., and Krueger, C.C. 1995. Recognition of spawning areas by lake trout: deposition and survival of eggs on small, man-made rock piles. J. Great Lakes Res. 21: 330-336. doi:10.1016/S0380-1330(95)71107-8.

Martens, A.M., Silins, U., Proctor, H.C., Williams, C.H.S., Wagner, M.J., Emelko, M.B., and Stone, M. 2019. Long-term impact of severe wildfire and post-wildfire salvage logging on macroinvertebrate assemblage structure in Alberta's Rocky Mountains. Int. J. Wildl. Fire 28(10): 738–749. doi:10.1071/WF18177.

McCann, K.S., 2011. Food webs (MPB-50). Princeton University Press.

McCook, L., Schaffelke, B., Apte, S., Brinkman, R., Brodie, J., Erftemeijer, P., Eyre, B., Hoogerwerf, F., Irvine, I., and Jones, R. 2015. Synthesis of current knowledge of the biophysical impacts of dredging and disposal on the Great Barrier Reef: report of an independent panel of experts. Great Barrier Reef Marine Park Authority. v + 97 p + Appendix A-G.

McCue, M.D. 2010. Starvation physiology: reviewing the different strategies animals use to survive a common challenge. Comp. Biochem. Physiol. Part A Mol. Integr. Physiol. 156(1): 1-18. doi:10.1016/j.cbpa.2010.01.002.

McGill, B.J., Enquist, B.J., Weiher, E., and Westoby, M. 2006. Rebuilding community ecology from functional traits. Trends Ecol. Evol. 21(4): 178-185. doi:10.1016/j.tree.2006.02.002.

McMeans, B.C., McCann, K.S., Guzzo, M.M., Bartley, T.J., Bieg, C., Blanchfield, P.J., Fernandes, T., Giacomini, H.C., Middel, T., Rennie, M.D., and Ridgway, M.S. 2020. Winter in water: differential responses and the maintenance of biodiversity. Ecol. Lett. 23(6): 922-938. doi:10.1111/ele.13504.

McMeans, B.C., McCann, K.S., Tunney, T.D., Fisk, A.T., Muir, A.M., Lester, N.P., Shuter, B.J., and Rooney, N. 2016. The adaptive capacity of lake food webs: from individuals to ecosystems. Ecol. Monogr. 95(4): 833–844. doi:10.1890/15-0288.1.

Meehan, W.R. 1991. Influences of forest and rangeland management on salmonid fishes and their habitats. Edited By W.R. Meehan. American Fisheries Society Special Publication 19, Bethesda, Maryland.

Meester, G.A., Ault, J.S., Smith, S.G., and Mehrotra, A. 2001. An integrated simulation modeling and operations research approach to spatial management decision making. Sarsia 86(6): 543-558. doi:10.1080/00364827.2001.10420492.

Méndez, G. and Wieser, W. 1993. Metabolic responses to food deprivation and refeeding in juveniles of Rutilus rutilus (Teleostei: Cyprinidae). Environ. Biol. Fishes 36(1): 73-81. doi:10.1007/BF00005981.

Midwood, J.D., Larsen, M.H., Aarestrup, K., and Cooke, S.J. 2016. Stress and food deprivation: linking physiological state to migration success in a teleost fish. J. Exp. Biol. 219(23): 3712-3718. doi:10.1242/jeb.140665.

Mims, M.C., Olden, J.D., Shattuck, Z.R., and Poff, N.L. 2010. Life history trait diversity of native freshwater fishes in North America. Ecol. Freshw. Fish 19(3): 390-400. doi:10.1111/j.1600-0633.2010.00422.x.

Minns, C.K., Randall, R.G., Moore, J.E., and Cairns, V.W. 1996. A model simulating the impact of habitat supply limits on northern pike, *Esox lucius*, in Hamilton Harbour, Lake Ontario. Can. J. Fish. Aquat. Sci. 53(S1): 20-34. doi:10.1139/cjfas-53-S1-20.

Moore, J.W., Mcclure, M., Rogers, L.A., and Schindler, D.E. 2010. Synchronization and portfolio performance of threatened salmon. Conserv. Lett. 3(5): 340–348. doi:10.1111/j.1755-263X.2010.00119.x.

Mundy, P.R. and Evenson, D.F. 2011. Environmental controls of phenology of high-latitude Chinook salmon populations of the Yukon River, North America, with application to fishery management. ICES J. Mar. Sci. 68(6): 1155-1164. doi:10.1093/icesjms/fsr080.

Nyboer, E.A., Lin, H.Y., Bennett, J.R., Gabriel, J., Twardek, W., Chhor, A.D., Daly, L., Dolson, S., Guitard, E., Holder, P., and Mozzon, C.M. 2021. Global assessment of marine and freshwater recreational fish reveals mismatch in climate change vulnerability and conservation effort. Glob. Chang. Biol. 27(19): 4799-4824. doi:10.1111/gcb.15768.

Nickelson, T.E. and Lawson, P.W. 1998. Population viability of coho salmon, Oncorhynchus kisutch, in Oregon coastal basins: application of a habitat-based life cycle model. Can. J. Fish. Aquat. Sci. 55(11): 2383–2392. doi:10.1139/f98-123.

National Research Council (NRC). 2001. A process for setting, managing, and monitoring environmental windows for dredging projects. Marine Board, Transportation Research Board, Special Report 262. Washington, D.C.: National Academy Press. ix + 37 p + Appendix A-E.

Ogle, S. 2005. A review of scientific information on the effects of suspended sediments on Pacific Herring (*Clupea pallasi*) reproductive success [Report]. Pacific Ecorisk: i + 21 p.

Olden, J.D., Poff, N.L., and Bestgen, K.R. 2008. Trait synergisms and the rarity, extirpation, and extinction risk of desert fishes. Ecology 89(3): 847-856. doi:10.1890/06-1864.1.

Paine, R.T., 1980. Food webs: linkage, interaction strength and community infrastructure. J. Anim. Ecol. 49(3): 667-685. doi:10.2307/4220.

Pascual, P., Pedrajas, J.R., Toribio, F., López-Barea, J., and Peinado, J. 2003. Effect of food deprivation on oxidative stress biomarkers in fish (*Sparus aurata*). Chem. Biol. Interact. 145(2): 191-199. doi:10.1016/S0009-2797(03)00002-4.

Pauly, D. and Pullin, R.S. 1988. Hatching time in spherical, pelagic, marine fish eggs in response to temperature and egg size. Environ. Biol. Fishes 22(4): 261-271. doi:10.1007/BF00004892.

Pentz, S.B. and Kostaschuk, R.A. 1999. Effect of placer mining on suspended sediment in reaches of sensitive fish habitat. Environ. Geol. 37(1–2): 78–89. doi:10.1007/s002540050363.

Pess, G.R. and Jordan, C.E. 2019. Characterizing watershed-scale effects of habitat restoration actions to inform life cycle models: case studies uing data-rich vs. data poor approaches. NOAA Technical Memorandum NMFS NWFSC: xv + 151 p. doi:10.25923/vka-w128.

Poff, N.L.R., Bledsoe, B.P., and Cuhaciyan, C.O. 2006. Hydrologic variation with land use across the contiguous United States: Geomorphic and ecological consequences for stream ecosystems. Geomorphology 79: 264–285. doi:10.1016/j.geomorph.2006.06.032.

Power, M.E., Tilman, D., Estes, J.A., Menge, B.A., Bond, W.J., Mills, L.S., Daily, G., Castilla, J.C., Lubchenco, J., and Paine, R.T., 1996. Challenges in the quest for keystones: identifying keystone species is difficult—but essential to understanding how loss of species will affect ecosystems. BioScience. 46(8): 609-620. doi:10.2307/1312990.

Radinger, J. and Wolter, C. 2014. Patterns and predictors of fish dispersal in rivers. Fish Fish. 15(3): 456-473. doi:10.1111/faf.12028.

Rainwater, C., Nachtmann, H., and Adbesh, F. 2016. Optimal dredge fleet scheduling within environmental work windows. MarTREC 5002 Final Research Report. iii + 47 p.

Rainwater, C., Nachtmann, H., and Adbesh, F. 2017. Optimal dredge fleet scheduling, phase 2. MarTREC 5010 Final Research Report. iii + 19 p.

Reid, D.A. and Hassan, M.A. 2020. Response of in-stream wood to riparian timber harvesting: field observations and long-term projections. Water Resour. Res. 56(8): 1–17. doi:10.1029/2020WR027077.

Reine, K., Clarke, D., Balzaik, M., O'Haire, S., Dickerson, C., Frederickson, C., Garman, G., Hager, C., Spells, A., and Turner, C. 2014. Assessing impacts of navigation dredging on Atlantic sturgeon (*Acipenser oxyrinchus*). Army Engineer Research and Development Center Vicksburg MS Environmental Lab.

Reine, K.J., Dickerson, D.D., and Clarke, D.G. 1998a. Environmental windows associated with dredging operations. US Army Engineer Waterways Experiment Station Vicksburg, MS.

Reine, K.J., Clarke, D.G., and Engler, R.M. 1998b. Entrainment by hydraulic dredges-A review of potential impacts. US Army Engineer Waterways Experiment Station Vicksburg, MS.

Rich, A. 2010. Potential impacts of re–suspended sediments associated with dredging and dredged material placement on fishes in San Francisco Bay, California—literature review and identification of data gaps. Army Corps of Engineers, San Francisco, California. vi + 75 p + Appendix A-M.

Rideout, R.M., Burton, M.P.M., and Rose, G.A. 2000. Observations on mass atresia and skipped spawning in northern Atlantic cod, from Smith Sound, Newfoundland. J. Fish Biol. 57(6): 1429-1440. doi:10.1111/j.1095-8649.2000.tb02222.x.

Roff, D.A. 1984. The evolution of life history parameters in teleosts. Can. J. Fish. Aquat. Sci. 41(6): 989-1000. doi:10.1139/f84-114.

Rogers, S.I. and Nicholson, M.D. (2002). Monitoring the outcome of a seasonal dredging restriction: a precautionary approach. Sci. Ser. Tech. Rep., CEFAS Lowestoft, 115: 5-11.

Rosenfeld, J.S. 2017. Developing flow–ecology relationships: implications of nonlinear biological responses for water management. Freshw. Biol. 62(8): 1305–1324. doi:10.1111/fwb.12948.

Rowe, S. and Hutchings, J.A. 2003. Mating systems and the conservation of commercially exploited marine fish. Trends Ecol. Evol. 18(11): 567-572. doi:10.1016/j.tree.2003.09.004.

Schindler, D.E., Hilborn, R., Chasco, B., Boatright, C.P., Quinn, T.P., Rogers, L.A., and Webster, M.S. 2010. Population diversity and the portfolio effect in an exploited species. Nature 465(7298): 609–612. doi:10.1038/nature09060.

Schreck, C.B. 2010. Stress and fish reproduction: the roles of allostasis and hormesis. Gen. Comp. Endocrinol. 165(3): 549-556. doi:10.1016/j.ygcen.2009.07.004.

Scott, W.B. and Crossman, E.J. 1998. Freshwater fishes of Canada. Galt House Publications Ltd, Oakville, Ontario.

Sesterhenn, T.M., Roswell, C.R., Stein, S.R., Klaver, P., Verhamme, E., Pothoven, S.A., and Höök, T.O. 2014. Modeling the implications of multiple hatching sites for larval dynamics in the resurgent Saginaw Bay walleye population. J. Great Lakes Res. 40: 113-122. doi:10.1016/j.jglr.2013.09.022.

Shuter, B.J. 1990, December. Population-level indicators of stress. In American Fisheries Society Symposium Vol. 8: 145-166.

Smokorowski, K., E. Bradford, M.J., Clarke, K.D., Clément, M., Gregory, R.S., and Randall, R.G. 2015. Assessing the effectiveness of habitat offset activities in Canada: monitoring design and metrics. Can. Tech. Rep. Fish. Aquat. Sci. 3132: vi + 48 p.

Smokorowski, K.E. and Pratt, T.C., 2006. Effect of a change in physical structure and cover on fish and fish habitat. Can. Tech. Rep. Fish. Aquat. Sci. 2642: iv + 52 p.

Springate, J.R.C., Bromage, N.R., Elliott, J.A.K., and Hudson, D.L. 1984. The timing of ovulation and stripping and their effects on the rates of fertilization and survival to eying, hatch and swim-up in the rainbow trout (*Salmo gairdneri* R.). Aquaculture 43(1-3): 313-322. doi:10.1016/0044-8486(84)90032-2.

St-Hilaire, A., Duchesne, S., and Rousseau A.N. 2016. Floods and water quality in Canada: a review of the interactions with urbanization, agriculture and forestry. Canadian Water Resources Journal / Revue canadienne des ressources hydriques, 41(1-2): 273-287. doi:10.1080/07011784.2015.1010181

Suedel, B.C., Kim, J., Clarke, D.G., and Linkov, I. 2008. A risk-informed decision framework for setting environmental windows for dredging projects. Sci. Total Environ. 403(1-3): 1-11. doi:10.1016/j.scitotenv.2008.04.055.

Suedel, B.C., Lutz, C.H., Clarke, J.U., and Clarke, D.G. 2012. The effects of suspended sediment on walleye (*Sander vitreus*) eggs. J. Soils Sediments. 12(6): 995-1003. doi:10.1007/s11368-012-0521-1.

Suedel, B.C., Clarke, J.U., Lutz, C.H., Clarke, D.G., Godard-Codding, C., and Maul, J. 2014. Suspended sediment effects on walleye (*Sander vitreus*). J. Great Lakes Res. 40(1): 141-148. doi:10.1016/j.jglr.2013.12.008.

Suedel, B.C., Clarke, J.U., Wilkens, J., Lutz, C.H., and Clarke, D.G. 2015. The effects of a simulated suspended sediment plume on eastern oyster (*Crassostrea virginica*) survival, growth and condition. Estuaries Coast. 38: 578-589. doi:10.1007/s12237-014-9835-0.

Suski, C.D. and Ridgway, M.S. 2009. Winter biology of centrarchid fishes. Centrarchid Fishes: Biology, Diversity, and Conservation. Blackwell-Wiley, Ames, IA. 264-292 p.

Todd, V.L., Todd, I.B., Gardiner, J.C., Morrin, E.C., MacPherson, N.A., DiMarzio, N.A., and Thomsen, F. 2015. A review of impacts of marine dredging activities on marine mammals. ICES J. Mar. Sci. 72(2): 328-340. doi:10.1093/icesjms/fsu187.

Tschaplinski, P.J. and Pike, R.G. 2017. Carnation Creek watershed experiment—long-term responses of coho salmon populations to historic forest practices. Ecohydrology 10(2): e1812. doi:10.1002/eco.1812.

Tsuda, Y., Kawabe, R., Tanaka, H., Mitsunaga, Y., Hiraishi, T., Yamamoto, K., and Nashimoto, K. 2006. Monitoring the spawning behaviour of chum salmon with an acceleration data logger. Ecol. Freshw. Fish. 15: 264-274. doi:10.1111/j.1600.0633.2006.00147.x

van der Lee, A.S. and Koops, M.A. 2015. Are small fishes more sensitive to habitat loss? A generic size-based model. Can. J. Fish. Aquat. Sci. 73(4): 716-726. doi:10.1139/cjfas-2015-0026.

van Overzee, H.M. and Rijnsdorp, A.D. 2015. Effects of fishing during the spawning period: implications for sustainable management. Rev. Fish Biol. Fish. 25(1): 65-83. doi:10.1007/s11160-014-9370-x.

Wang, T., Hung, C.C. and Randall, D.J. 2006. The comparative physiology of food deprivation: from feast to famine. Annu. Rev. Physiol. 68: 223-251. doi:10.1146/annurev.physiol.68.040104.105739.

Weaver, D.M., Kwak, T.J., and Pollock, K.H. 2014. Sampling characteristics and calibration of snorkel counts to estimate stream fish populations. N. Am. J. Fish. Manag. 34(6): 1159-1166. doi:10.1080/02755947.2014.951808.

Wehner, C.E. and Stednick, J.D. 2017. Effects of mountain pine beetle-killed forests on source water contributions to streamflow in headwater streams of the Colorado Rocky Mountains. Front. Earth Sci. 11(3): 496–504. doi:10.1007/s11707-017-0660-1.

Weis, J.J. and Sass, G.G. 2011. Largemouth bass nest site selection in small, north temperate lakes varying in littoral coarse woody habitat abundances. N. Am. J. Fish. Manag. 31(5): 943-951. doi:10.1080/02755947.2011.633688.

Werner, E.E. and Gilliam, J.F. 1984. The ontogenetic niche and species interactions in size-structured populations. Annu. Rev. Ecol. Evol. Syst. 15(1): 393-425. doi:10.1146/annurev.es.15.110184.002141.

Weißhuhn, P., Müller, F., and Wiggering, H. 2018. Ecosystem vulnerability review: proposal of an interdisciplinary ecosystem assessment approach. Environ. manage. 61(6): 904-915. doi:10.1007/s00267-018-1023-8.

Whitney, E. J., Bellmore, J. R., Benjamin, J. R., Jordan, C. E., Dunham, J. B., Newsom, M., and Nahorniak, M. 2020. Beyond sticks and stones: Integrating physical and ecological conditions into watershed restoration assessments using a food web modeling approach. Food Webs, 25: e00160. doi:10.1016/j.fooweb.2020.e00160.

Wilson, S.K., Burgess, S.C., Cheal, A.J., Emslie, M., Fisher, R., Miller, I., Polunin, N.V.C., and Sweatman, H.P.A. 2008. Habitat utilization by coral reef fish: implications for specialists vs. Generalists in a changing environment. J. Anim. Ecol. 77: 220-228. doi:10.1111/j.1365-2656.2007.01341.x.

Wickliffe, L.C., Rohde, F.C., Riley, K.L., and Morris, J.A. (eds.) 2019. An assessment of fisheries species to inform time-of-year restrictions for North Carolina and South Carolina. NOAA Technical Memorandum NOS NCCOS: xv + 241 p + Appendix A.

Winemiller, K.O. 2005. Life history strategies, population regulation, and implications for fisheries management. Can. J. Fish. Aquat. Sci. 62(4): 872-885. doi:10.1139/f05-040.

Wohl, E., Kramer, N., Ruiz-Villanueva, V., Scott, D.N., Comiti, F., Gurnell, A.M., Piegay, H., Lininger, K.B., Jaeger, K.L., Walters, D.M., and Fausch, K.D. 2019. The natural wood regime in rivers. Bioscience 69(4): 259–273. doi:10.1093/biosci/biz013.

Wright, S., Metcalfe, J.D., Hetherington, S., and Wilson, R., 2014. Estimating activity-specific energy expenditure in a teleost fish, using accelerometer loggers. Marine Ecol. Prog. Series, 496: 19-32. doi:10.3354/meps10528.

Wu, P.P.-Y., Mengersen, K., McMahon, K., Kendrick, G.A., Chartrand, K., York, P.H., Rasheed, M.A., and Caley, M.J. 2017. Timing anthropogenic stressors to mitigate their impact on marine ecosystem resilience. Nat. Commun. 8(1): 1-11. doi:10.1038/s41467-017-01306-9.

Zhao, Y., Shuter, B.J., and Jackson, D.A. 2008. Life history variation parallels phylogeographical patterns in North American walleye (Sander vitreus) populations. Can. J. Fish. Aquat. Sci. 65(2): 198-211. doi:10.1139/f07-162.

Zuckerman, Z.C., and Suski, C.D. 2013. Predator burden and past investment affect brood abandonment decisions in a parental care-providing teleost. Funct. Ecol. 27(3): 693-701. doi:10.1111/1365-2435.12074.

APPENDIX A. GLOSSARY

Table of definitions for terms used in this document.

Term	Description	Reference
Before-After-Control-Impact (BACI)	A study design which involves before and after monitoring in a control and impact site.	Braun et al. 2019
Consistency	The ability of an action to produce the same outcome with repeated application.	Tunney et al. 2017
Compliance Monitoring	A monitoring program that monitors the WUA operations and whether regulations are being followed.	DFO 2012b
Effectiveness (*mitigation measure)*	For a mitigation whether the measure produces the expected (or intended) outcome when it is applied.	Cormier et al. 2017
Effectiveness Monitoring	A scientifically defensible monitoring program that directly assess a key metric or indicator of interest, which may include productive capacity or a surrogate of the offsetting or compensation.	DFO 2012b
Endpoints	Change to fish populations or fish habitat caused by a WUA through one or more pathways.	Brownscombe and Smokorowski 2021
Entrainment	Direct uptake of aquatic organisms by suction field of the dredge	Reine et al. 1998a; See Page 9
Functional Monitoring	A less intensive approach compared to effectiveness monitoring that focuses on measurement of physical and chemical components of habitat.	DFO 2019b
Habitat	Areas of an organism's environment that are used and needed for critical life processes, like spawning and feeding.	Braun et al. 2019
Mitigation	"Is a measure to reduce the spatial scale, duration, or intensity of serious harm to fish that cannot be completely avoided."	Braun et al. 2019; DFO 2019a
Phenology	The study of the timing of natural events.	Mundy and Evenson 2011
Persistence	The time needed for any pressure to disappear, starting with the time a WUA begins to change a habitat component, to the time the pressure is no longer present.	See Page 37
Pressures	Human driven change in any chemical, physical or biological entity that can cause an effect on fish and/or fish habitat which may lead to harm.	Brownscombe and Smokorowski 2021
Rationale	A set of reasons or logical basis for a course of action. Used here in reference to the creation and/or modification of a mitigation measure (e.g., a timing window).	See Page 4
Continuing Pressure	A component of WUA persistence that describes the *pressure* that persists after the WUA concludes.	See Figure 10 (See Page 37)

Term	Description	Reference
Resilience	A measure of the persistence of systems and of their ability to absorb change and disturbance and still maintain the same relationships between populations or state variables.	Holling 1973
Restricted Activity Periods	Periods in the year when WUAs cannot occur due to an elevated risk of harm to fish and fish habitat	FFHPP, CSAS request
Risk	(1) Uncertainty of outcome and probability the outcome will occur. (2) Uncertainty and magnitude of outcome from an event.	Bradford et al. 2015
Suitability	Appropriateness of a timing window for mitigating negative impacts from a WUA on a life process based on the characteristics of that life process.	See Page 28
Timing Window (OR Environmental Window, Work Window)	A mitigation measure that define periods in the year when work can occur with reduced risk of negative impacts on fish and fish habitat, and consequently, critical life processes of fish (e.g., spawning, migration, natal and rearing, feeding, and refuge use)	See Page 1
Vulnerability	Likelihood of a negative effect on a life or habitat process exposed a WUA pressure (i.e., its susceptibility) and the ability of the process to recover after an impact	Weißhuhn et al. 2018

APPENDIX B. SUPPLEMENTARY INFORMATION

B.1. LITERATURE SEARCH TERMS

Table SI-1. Search terms used in the 15 paired Google Scholar/Web of Science searches and the 27 government database searches. Different search term combinations were used. Search strings were created using the "AND" operator between categories and "OR" within categories.

Categories	Terms
Study Organism	"Fish" OR "Species at Risk" OR "Invertebrate" OR "Zooplankton" OR "Mussel"
Habitat	"Freshwater" OR "Estuaries" OR "Lake" OR "Creek" OR "River" OR "Stream" OR "Pond" OR "Habitat" OR "Wetland" OR "Riparian" OR "Waterway"
WUA (Works, Undertakings or Activities)	"Dredg*" OR "Culverts" OR "Bridge" OR "Pipeline" OR "Hydrostatic" OR "Development" OR "Mining" OR "Dams" OR "Construction" OR "Excavation" OR "Grading" OR "Land clearing" OR "Trenches" OR "Outfall structure" OR "Machinery" OR "Explosives" OR "Wastewater" OR "Alteration" OR "Impacts" OR "Degradation" OR "Pile driving" OR "Drilling"
Pressure	"Sediment*" OR "Suspended" OR "Erosion" OR "Compaction" OR "Nutrient change" OR "Nutrient Influxes" OR "Channel morphology" OR "Shoreline change" OR "Vegetation clearing" OR "Altered vegetation" OR "Herbicide" OR "Pesticide" OR "Bank alteration" OR "Changes to drainage" OR "Water quality" OR "Oil" OR "Fuel" OR "Trampling" OR "Water diversion" OR "Nutrient loading"
Life Stages/Processes	"Spawn*" OR "Breed*" OR "Migrat*" OR "Incubat*" OR "Egg viability" OR "Hatch*" OR "Egg Adhesion" OR "Larvae" OR "Fry" OR "Fingerling" OR "Movement" OR "Habitat" OR "Mortality" OR "Recruitment" OR "Feed*" OR "Prey" OR "Interactions" OR "Recovery" OR "Nursery" OR "Rearing" OR "Physical injury" OR "Stranding" OR "Decrease food supply" OR "Productivity" OR "Communication"
Mitigation Measure	"Timing Window" OR "Restricted Activity Period" OR "Work Window" OR "Environmental Window" OR "Ecological window" OR "Closure"

B.2. LITERATURE REVIEW LIST

Table SI-2. List of 110 documents found during the timing windows literature search and review. Documents concerning the use and effectiveness of timing windows that specifically mentioned "timing windows" or an equivalent concept were used.

Year	Authors	Title
2017	Adbesh	Methodologies for Solving Integrated Transportation and Scheduling Problems
2003	Anchor Environmental	Literature review of effects of resuspended sediments due to dredging operations
1998	Ault et al.	FISHFATE: Population Dynamics Models to Assess Risks of Hydraulic Entrainment by Dredges
1999	Ault et al.	Users guide for FISHFATE vers. 1.0: A spatially-explicit model for simulating population responses to alternative dredge entrainment scenarios.
2020	Balazik et al.	Dredging activity and associated sound have negligible effects on adult Atlantic sturgeon migration to spawning habitat in a large coastal river
2021	Balazik et al.	Atlantic sturgeon movements in relation to a cutterhead dredge in the James River, Virginia
2015	Barnucz et al.	Impacts of dredging on fish species at risk in Lake St. Clair, Ontario
2001	Bash et al.	Effects of turbidity and suspended solids on salmonids
2011	Berry et al.	Assessment of dredging-induced sedimentation effects on winter flounder (*Pseudopleuronectes americanus*) hatching success: results of laboratory investigations.
2002	Burt	Environmental windows as emerging issues in Europe
2004	Burt and Hayes	Framework for research leading to improved assessment of dredge generated plumes
1986	Carter	An argument for retaining periods of non-dredging for the protection of oyster resources in upper Chesapeake Bay
2009	Chapman et al.	Juvenile salmonid outmigration and green sturgeon distribution in the San Francisco Estuary
2019	Chapman et al.	Spatiotemporal occurrence of green sturgeon at dredging and placement sites in the San Francisco estuary
1992	Chilibeck et al.	Land development guidelines for the protection of aquatic habitat
2000	Clarke et al.	Assessment of Potential Impacts of Dredging Operations Due to Sediment Resuspension.
2003	Clarke et al.	Dredging Operations and Environmental Research Program: Building Tools for Objective Determination of Environmental Windows
2005	Connor et al.	Potential impacts of dredging on pacific herring in San Francisco Bay
2015a	DFO	Proceedings of the regional science peer review of impacts of dredging on fish species at risk in the lower Great Lakes basin

Year	Authors	Title
2015b	DFO	Assessment of the impacts of dredging on fish species at risk in lake St. Clair, Ontario (SAR 2015/50)
1998	Dickerson and Nelson	Proceedings of the national workshop on methods to minimize dredging impacts on sea turtles
1995	Dickerson et al.	Assessment of sea turtle abundance in six south Atlantic U.S. channels to evaluate species composition, population structure, and spatial and temporal distributions
1998	Dickerson et al.	Economic impacts of environmental windows associated with dredging operations
2001	Dickerson et al.	Characterization of underwater sounds produced by bucket dredging operations
2004	Dickerson et al.	Dredging impacts on sea turtles in the Southeastern USA: a historical review of protection
2007	Dickerson et al.	Effectiveness of relocation trawling during hopper dredging for reducing incidental take of sea turtles
2018	Dredged Material Management Office (DMMO)	Dredging and placement of dredged material in San Francisco Bay January-December 2017 report
2009	ECORP Consulting Inc	Literature review (for studies conducted prior to 2008): fish behavior in response to dredging & dredged material placement activities
2020	Elko et al.	Best management practices for coastal inlets
2016	Feola et al.	Platform of integrated tools to support environmental studies and management of dredging activities
2005	Francingues and Palmero	Silt curtains as a dredging project management practice
2017	Fraser et al.	Effects of dredging on critical ecological processes for marine invertebrates, seagrasses and macroalgae, and the potential for management with environmental windows using Western Australia as a case study
2004	Goodchild	Fish habitat is everyone's business, Canada's fish habitat management programme
1994	Goodchild and Metikosh	Fisheries-related information requirements for pipeline water crossings
2021	Great Lakes Commission	Exploring science-based strategies for environmental dredging windows in Lake Michigan
2009	Griffin et al.	Impacts of suspended sediments on fertilization, embryonic development, and early larval life stages of the Pacific herring
2008	Griffin et al.	Impacts of suspended sediments on fertilization, embryonic development and early larval stages of the Pacific Herring, *Clupea pallasi* (Full Report)
2012	Griffin et al.	Larval Pacific Herring (*Clupea pallasi*) Survival in Suspended Sediment
nd	Griffin et al.	Impacts of suspended sediments in San Francisco Bay on Pacific Herring larval survival condition
2000	Hales et al.	Dredging Research

Year	Authors	Title
2017	Harvey et al.	Effects of dredging-related pressures on critical ecological processes for finfish: a review and possible management strategies
2010	Hearn et al.	Juvenile salmonid outmigration and green sturgeon distribution in the San Francisco Estuary Annual report 2010
2005	Hoover et al.	Paddlefish and sturgeon entrainment by dredges: swimming performance as an indicator of risk
2008	Jabusch	Effects of short-term water quality impacts due to dredging and disposal on sensitive fish species in San Francisco Bay
2002	James et al.	Re: Timing Windows and Measures for the Conservation of Fish and Fish Habitat for the Omineca Region
2004	James et al.	Re: Reduced Risk Timing Windows and Measures for the Conservation of Fish and Fish Habitat for the Omineca Region
2000a	Johnson et al.	Description of the SSFATE numerical modeling system
2000b	Johnson et al.	Demonstration of the SSFATE numerical modeling system
1997	Keevin and Hempen	The environmental effects of underwater explosions with methods to mitigate impacts
2015	Kjelland et al.	A review of the potential effects of suspended sediment on fishes: potential dredging-related physiological, behavioral, and transgenerational implications
2009	Klimley et al.	Juvenile salmonid outmigration and distribution in the San Francisco estuary: 2006-2008 interim draft report
2016	Krebs et al.	Avoidance of pile-driving noise by Hudson River sturgeon during construction of the new NY Bridge at Tappan Zee
1992	LaSalle et al.	Seasonal restrictions on dredging: an approach toward issue resolution
1991	LaSalle et al.	A framework for assessing the need for seasonal restrictions on dredging and disposal operations
2013	Leslie and Schertner	Reducing Inwater Pile Driving Sound-What Are My Options?
2004	Levine-Fricke	Framework for assessment of potential effects of dredging on sensitive fish species in San Francisco Bay
2001	Long-term Management Strategy (LTMS)	Long-term management strategy for the placement of dredged material in the San Francisco Bay region
2012a	LTMS	Long-term management strategy for the placement of dredged material in the San Francisco Bay region, 12-year review final report
2012b	LTMS	Long-term management strategy for the placement of dredged material in the San Francisco Bay region, 12-year review process Appendix D
2012c	LTMS	San Francisco Bay long-term management strategy program 12-year review
2012d	LTMS	San Francisco Bay long-term management strategy program 12-year review Appendix A Program data assessment meeting materials package

Year	Authors	Title
2012e	LTMS	San Francisco Bay long-term management strategy program 12-year review Appendix F
1984	Lunz et al.	Seasonal Restrictions on bucket dredging operations in freshwater systems
2012	Lutz et al.	A fish larvae and egg exposure system (FLEES) for evaluating the effects of suspended sediments on aquatic life
2015	McCook et al.	Synthesis of current knowledge of the biophysical impacts of dredging and disposal on the Great Barrier Reef: report of an independent panel of experts
2001	Meester et al.	An integrated simulation modeling and operations research approach to spatial management decision making
2017	Montgomery et al.	A Modelling-based Assessment of the Impacts of Drain Maintenance on Fish Species-at-risk Habitat in Little Bear Creek, Ontario
2014	Natchmann et al.	Optimal Dredge Fleet Scheduling Within Environmental Work Windows
2001	National Research Committee (NRC)	A process for setting, managing, and monitoring environmental windows for dredging projects
2015	NMFS	Endangered Species Act (ESA) Section 7(a)(2) Biological opinion: long term management strategy for the placement of dredged material in the San Francisco Bay Region
2004	Ogle	A bibliography of scientific literature on Pacific Herring (*Clupea pallasi*), with additional selected references for Baltic herring (*Clupea harengus*)
2005	Ogle	A review of scientific information on the effects of suspended sediments on pacific herring (*Clupea pallasi*) reproductive success
2008	Palermo et al	Technical guidelines for environmental dredging of contaminated sediments
2016	Rainwater et al.	Optimal dredge fleet scheduling within environmental work windows
2017	Rainwater et al.	Optimal Dredge Fleet Scheduling, Phase 2
2016	Reid et al.	Seasonal variation in the composition of fishes caught during trawl-based surveys of Little Bear Creek, Ontario
2014	Reine et al.	Assessing impacts of navigation dredging on Atlantic Sturgeon (*Acipenser oxyrinchus)*
2007	Reine et al.	Assessment of potential impacts of bucket dredging plumes on walleye spawning habitat in Maumee Bay, Ohio
1998a	Reine et al.	Entrainment by hydraulic dredges-A review of potential impacts
1998b	Reine et al.	Environmental Windows Associated with Dredging Operations
2010	Rich	Potential impacts of re–suspended sediments associated with dredging and dredged material placement on fishes in San Francisco Bay, California—Literature review and identification of data gaps
2011	Rich	Tools for assessing and monitoring fish behavior caused by dredging activities
2011	Robinson and Greenfield	LTMS longfin smelt literature review and study plan

Year	Authors	Title
2002	Rogers and Nicholson	Monitoring the outcome of a seasonal dredging restriction: a precautionary approach
1989	Sanders and Killgore	Seasonal restrictions on dredging operations in freshwater systems
2011	Schultz and Borrowman	Bayesian networks for modelling dredging decisions
2017	Short et al.	Effects of dredging-related pressures on critical ecological processes for organisms other than fish or coral
1988	Simenstad	Effects of dredging on anadromous Pacific coast fishes
2019	Suedel and Fischer	Future Directions of Threatened and Endangered Species and Environmental Windows Research within the Dredging Operations and Environmental Research Program
2019	Suedel et al.	Evaluating effects of dredging-induced underwater sound on aquatic species
2008	Suedel et al.	A risk-informed decision framework for setting environmental windows for dredging projects
2012	Suedel et al.	The effects of suspended sediment on walleye (*Sander vitreus*) eggs
2014	Suedel et al.	Suspended sediment effects on walleye (*Sander vitreus*)
2015	Suedel et al.	The effects of a simulated suspended sediment plume on eastern oyster (*Crassostrea virginica*) survival, growth, and condition
2017	Suedel et al.	Effects of Suspended Sediment on Early Life Stages of Smallmouth Bass (*Micropterus dolomieu*)
2015	Todd et al.	A review of impacts of marine dredging activities on marine mammals
2021	Tomlin et al.	Identifying and monitoring of forage fish spawning beaches in British Columbia's Salish Sea for conservation of forage fish
2004	USACE	Long Term Management Strategy (LTMS) Environmental Work Windows: Informal Consultation Preparation Packet
2009	USACE	Programmatic essential fish habitat (EFH) assessment for the long-term management strategy for the placement of dredged material in the San Francisco Bay region
2013	USACE	Application of winter flounder early life history data to seasonal dredging constraints and essential fish habitat designations
2003	Vogt et al.	The National Dredging Team's Action Agenda: Issues and Actions for the Next Decade
1992	Washington et al.	Success and failures of acoustics in the measurement of environmental impacts
2016	Welch et al.	A literature review of the beneficial use of dredged material and sediment management plans and strategies
2018	Wenger et al.	Management strategies to minimize the dredging impacts of coastal development on fish and fisheries
2015	Wickliffe et al.	An assessment of fisheries species to inform time-of-year restrictions for North Carolina and South Carolina

Year	Authors	Title
2005	Wilber et al.	Sedimentation: Potential Biological Effects of Dredging Operations in Estuarine and Marine Environments
2017a	Wilkens and Suedel	A method for simulating sedimentation of fish eggs to generate biological effects data for assessing dredging impacts
2017b	Wilkens and Suedel	Using the Fish Larvae and Egg Exposure System (FLEES) to Generate Effects Data for Informing Environmental Windows
2015	Wilkens et al.	Laboratory test of suspended sediment effects on short-term survival and swimming performance of juvenile Atlantic sturgeon (*Acipenser oxyrinchus oxyrinchus*, Mitchill, 1815)
2017	Wu et al.	Timing anthropogenic stressors to mitigate their impact on marine ecosystem resilience

B.3. CANADIAN TIMING SOURCES

The information for the Canadian Timing Window summary was found on the *Fisheries and Oceans Canada- Projects near water* website which provided links to provincial/territorial documents and/or websites which were used in our search.

Table SI-3. A list of documents that were sourced in addition to the online resources mentioned above.

Province/Territory	Resources
Alberta	"Restricted Activity (RAPs) for Fish Species in 10 Fish Management Zones of Alberta", "Restricted Activity Period Fact Sheet"
British Columbia	"Timing windows and measures to adequately manage and conserve aquatic resources for the forest districts in the Cariboo Region"
Manitoba	"Appendix 10: DFO Operational Statements: Manitoba Operational Statement", "Enbridge Pipelines Inc. - Line 3 replacement project Commitments Tracking Table"
Northwest Territories	“Northwest Territories in water construction timing windows for protection of fish and fish habitat, "Inuvik to Tuktoyaktuk Highway: FFHPP Final Draft"
Nova Scotia	"Guide to Altering Watercourses by the Province of Nova Scotia"
Prince Edward Island	“Watercourse, Wetland and Buffer Zone Activity Guidelines, Version 3”
Saskatchewan	"Saskatchewan activity restriction guidelines for sensitive species"
Yukon	"Preferred practices for works affecting Yukon waters"

B.4. CANADIAN TIMING WINDOW SPECIES

Table SI-4. List of the fish species that are included within the Canadian timing windows documents from the Fisheries and Oceans Canada- Projects near water website and the documents listed in Appendix B Section 10.2.3 (Table SI-3).

Province/Territory	Species Mentioned in Freshwater Timing Window Documentation
Alberta	Arctic Grayling, Cutthroat Trout, Brook Trout, Brown Trout, Bull Trout, Lake Whitefish, Mountain Whitefish, Rainbow Trout, Burbot, Goldeye, Lake Sturgeon, Northern Pike, Yellow Perch, Sauger, Walleye
British Columbia	Green Sturgeon (Red Listed), Eulachon (Blue Listed), Steelhead, Rainbow Trout, Cutthroat Trout, Coastal Trout, Dolly Varden, Bull Trout, Lake Trout, Brook Trout, Chinook Salmon, Chum Salmon, Coho Salmon, Mountain Whitefish, Chiselmouth, Pink Salmon, Kokanee, Sockeye Salmon, Burbot, Lake Whitefish, other whitefish species, Arctic Grayling, Broad Whitefish (Red Listed), Least Cisco (Blue Listed), Giant Black Stickleback (Red Listed), Enos Lake Limnetic Stickleback (Red Listed), Cowichan Lake Lamprey (Red Listed), Morrison Creek Lamprey (Red Listed), Pacific salmon
Manitoba	Northern Pike, Walleye, Sauger, Yellow Perch, suckers, Smallmouth Bass, Arctic Grayling, Channel Catfish, Lake Sturgeon, Goldeye, Mooneye, White Bass, Freshwater Drum, Carmine Shiner (SAR), Brook Trout, Lake Trout, Arctic Char, Lake Whitefish *
New Brunswick	Shortnose Sturgeon, Atlantic Sturgeon, Blueback Herring, American Shad, Alewife, Gaspereau, Rainbow Trout, Atlantic Salmon, Brown Trout, Brook Trout, Lake Whitefish, Arctic Char, Chain Pickerel, Rainbow Smelt, Fourspine Stickleback, Brook Stickleback, White Perch, Yellow Perch, Smallmouth Bass, Atlantic Tomcod, American Eel, White Sucker *
Newfoundland & Labrador	Atlantic Salmon, Brown Trout
Northwest Territories	Arctic Grayling, Northern Pike, Walleye, Yellow Perch, Goldeye, Rainbow Smelt, Longnose Sucker, White Sucker *
Nova Scotia	Salmonids (and Alewife, American Shad, Rainbow Smelt *)
Nunavut	Arctic Char, Lake Trout, Broad Whitefish, Lake Whitefish, Round Whitefish, Arctic Grayling, Northern Pike *
Ontario	Walleye, Northern Pike, Lake Sturgeon, Muskellunge, Largemouth Bass, Smallmouth Bass, Rainbow Trout, Lake Trout, Brook Trout, Pacific salmon, Lake Whitefish, lake herring, otherother/unknown spring or fall spawning species
Prince Edward Island	Salmonids, Gaspereau, smelts *
Quebec	Atlantic Salmon/landlocked salmon, Lake Whitefish, Brook Trout, Lake Trout, Brown Trout, Rainbow Trout, Smallmouth Bass, Largemouth Bass, Striped Bass, Walleye, Sauger, Rainbow Smelt, Northern Pike, Muskellunge, Yellow Perch
Saskatchewan	Arctic Grayling, bullhead, Goldeye, Lake Sturgeon, Mooneye, Northern Pike, Rainbow Trout, Sauger, Smallmouth Bass, Suckers, Walleye, Yellow Perch, Brook Trout, Brown Trout, Burbot, Cisco, Lake Trout, whitefish *
Yukon	Chinook Salmon, Sockeye Salmon, Coho Salmon, Chum Salmon, Rainbow Trout, Lake Trout, Dolly Varden, Lake Trout, whitefish, Arctic Grayling, Bull Trout, Northern Pike

* Species are listed in timing window document, but it is not explicit if windows were developed considering the sensitive periods of species

B.5. CANADIAN MARINE TIMING WINDOWS

Table SI-5. List of the marine timing windows that are accessible from the Canadian timing windows documents from the Fisheries and Oceans Canada- Projects near water website. Note that information on marine timing windows was not available for all provinces and territories. Some are landlocked.

Province/ Territory	Identified WUAs	Identified Pressures	Window Type	Protected Life Stages/ Behaviours	Spatial Scale	Biological Scale	# of Unique Timing Windows*
BC	n/a	n/a	Timing Window	N/A	Estuaries, Regional/ Subregional	Species	21(104)
QC	n/a	n/a	Timing Window	spawning, migration, egg incubation, aggregation of young	Estuaries, Regional/ Subregional	Species	62 (146)
NL	n/a	n/a	Restricted Activity Period	migration, spawning, egg incubation and hatching	Estuaries, Regional (Newfoundland /Labrador)	Species	2

*the number of Unique Timing Windows (a range of unique dates for the whole province or territory) is listed first, followed by the total number of Timing Windows (refers to a unique combination of date, location and species for each province and territory) in parenthesis.