Fisheries and Oceans Canada
Canada

Pêches et Océans
Canada

Ecosystems and
Oceans Science

Sciences des écosystèmes
et des océans

Canadian Science Advisory Secretariat (CSAS)

Research Document 2021/079

National Capital Region

Review of Pathways of Effects (PoE) diagrams in support of FFHPP risk assessment

Jacob W. Brownscombe[1], Karen E. Smokorowski[2]

[1] Fisheries and Oceans Canada, Great Lakes Laboratory for Fisheries and Aquatic Sciences,
867 Lakeshore Rd, Burlington, ON, L7S 1A1, Canada

[2] Fisheries and Oceans Canada, Great Lakes Laboratory for Fisheries and Aquatic Sciences,
1219 Queen St. E., Sault Ste. Marie, ON, P6A 2E5, Canada

December 2021

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.

Published by:

Fisheries and Oceans Canada
Canadian Science Advisory Secretariat
200 Kent Street
Ottawa ON K1A 0E6

http://www.dfo-mpo.gc.ca/csas-sccs/
csas-sccs@dfo-mpo.gc.ca

ISSN 1919-5044
ISBN 978-0-660-41277-1 Cat. No. Fs70-5/2021-079E-PDF

Correct citation for this publication:

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.

Aussi disponible en français :

Brownscombe, J.W., Smokorowski, K.E. 2021. Examen des diagrammes de séquence des effets (SE) à l’appui de l’évaluation des risques du PPPH. Secr. can. de consult. sci. du MPO, Doc. de rech. 2021/079. iv + 61 p.

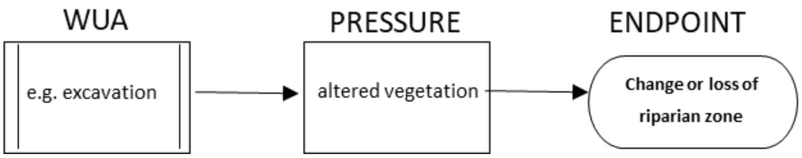
TABLE OF CONTENTS

ABSTRACT

Fisheries and Oceans Canada's Fish and Fish Habitat Protection Program (FFHPP) has a regulatory regime in place to avoid, mitigate and offset the negative effects of projects on fish and fish habitat. To understand these negative effects, Pathways of Effects (PoE) diagrams are used to describe linkages between the works, undertakings, and activities (WUAs), the 'pressures' by which WUAs affect the ecosystem, and the resulting 'endpoints' affecting fish and/or fish habitat. Twenty original PoE diagrams have been recently combined into four proposed diagrams focused on 1) land-based WUAs, 2) energy and noise producing WUAs, 3) in-water WUAs, and 4) WUAs affecting water flow. Here we provide a selective review of these four PoE diagrams to assess whether the pressures, pathways, and endpoints are valid, comprehensive, and complete. A range of support levels were found for pressure pathways, identifying well supported connections, those that have a theoretical basis but lack extensive research, those with potential alterations for improved comprehensiveness and accuracy, and those lacking support. Numerous recommendations are included for alterations to terminology and addition or removal of linkages and nodes. Related resources are included in a database that may serve to support the application and further development of additional PoE diagrams. It is challenging to encompass the wide variety of complex impacts that human activities may have on fish and fish habitat, and we recognize a trade-off between the comprehensiveness and tractability of these diagrams in communication and decision making. Consideration of this trade-off while integrating these recommendations is important to ensure maximum validity and applicability by FFHPP. To employ ecosystem-based management accounting for the cumulative effects of activities on ecosystem state, there is a need to further identify interconnectivity amongst these PoE diagrams, as well as how various pressure pathways interact to produce cumulative effects.

CONTEXT

Fisheries and Oceans Canada (DFO)`s Fish and Fish Habitat Protection Program (FFHPP) has a regulatory regime in place to avoid, mitigate and offset the negative effects of projects on fish and fish habitat. In order to understand these negative effects, linkages need to be made between the works, undertakings and activities (WUAs; see DFO (2021) for definitions), the ‘pressure’ by which WUAs affect the ecosystem, and the resulting ‘endpoints’ affecting fish and fish habitat (Figure 1).



Term	Definition
Works, undertakings and activities (WUAs)	Human actions that may impose pressures on fish and fish habitat
Pressure	A human driven change in any chemical, physical, or biological entity that can cause an effect on fish and/or fish habitat and may lead to harmful impacts.
Endpoint	Measurable change to fish populations or fish habitat components caused by a WUA through one or more pathways
Linkage	Directional connection between a WUA, pressure node, or endpoint
Pressure pathway	A series of linkages from a WUA(s) to pressure nodes, terminating at endpoints

Figure 1: Example of an individual linkage within a Pathway of Effects diagram including the work undertaking and activity (WUA), pressure, and endpoint affecting fish and fish habitat. Definitions of key terms included.

The FFHPP relies upon existing Pathways of Effects (PoE) diagrams to support regional practitioners in identifying and communicating the effects of proposed WUAs on fish and/or fish habitat. Through changes to the modernized *Fisheries Act* in 2019, the FFHPP now has a higher regulatory standard through which proposed WUAs are reviewed. However, there are concerns that existing PoE diagrams cannot be applied in a consistent manner in support of the regulatory review of projects, and in the assessment of their associated risks to fish and fish habitat. To effectively manage fish and fish habitat, it will be necessary to have scientifically validated PoE diagrams for common WUA categories that will enable their consistent use for the assessment of effects nationally.

To facilitate the consistent assessment of projects under the *Fisheries Act*, FFHPP has reworked existing PoE diagrams and consolidated them into fewer diagrams that align with their categories of WUAs. The original 20 diagrams (see **APPENDIX**: Table 1A) were simplified and consolidated into four categories: 1) land-based WUAs, 2) noise and energy producing WUAs 3) in-water WUAs, and 4) WUAs affecting flow. It is thus important to ensure that the pathways and linkages to resulting endpoints on fish and fish habitat are accurate, valid, comprehensive, and complete. The restructured and validated PoE diagrams, and the standardization of their use, will help determine where a project fits in the FFHPP Risk Management Framework, and ultimately whether the project requires a non-regulatory (e.g., letter of advice), or regulatory (e.g., authorization) instrument.

DFO's FFHPP has therefore requested the Canadian Science Advice Secretariat (CSAS) to conduct a peer review of the revised PoE diagrams, including consideration of their redesign, validation of existing linkages, and assessment of completeness. Revised and validated PoE diagrams may allow the FFHPP to consider impacts of project types in a consistent manner, and to understand the effects of a project at the site and ecosystem level. This will help ensure that fish and fish habitat are conserved and protected consistently across the country. **The objective of this document is to review the recently proposed PoE diagrams to assess whether the pressures, pathways, and endpoints are valid, comprehensive, and complete.**

APPROACH

We conducted a review of the accuracy and completeness of the four draft PoE diagrams through a literature search using Google, Google Scholar, and Open Government Portal. A hierarchical search approach was used, focused on combinations of keywords related to the activities, pressures, and endpoints ranging from general combinations of keywords to specific combinations that spanned the pressure pathways. For example, to explore the literature surrounding the pressure pathway from input of organic matter -> decrease in habitat access -> change or loss of fish passage, general keywords were searched such as 'coarse wood* fish habitat', as well as more specific combinations such as 'coarse wood* fish passage'. In doing so, we aimed to identify support, or lack thereof, for specific pathways, as well as connections, pressures, activities, or endpoints that are not currently included. A systematic review of a topic this large and complex was not possible due to resource constraints, hence this work takes the form of a selective, narrative-style review. Through this review, we identified pathways with varied levels of support or in need of some additions or alterations, identifying each pathway as a specific numeric category (Table 1). Supporting literature referenced here is included in an associated spreadsheet database.

Table 1: Categories of pathways identified based on levels of support

Category	***Description***
I	*Strong, direct basis of support in scientific literature linking the pressure pathway to the endpoint, including numerous, robust studies and/or syntheses or metanalyses*
II	*Direct basis of support in scientific literature linking the pressure pathway to the endpoint based on at least one robust study*
III	*Theoretical basis of support linking the pressure pathway to the endpoint, but no direct scientific evidence*
*	*In combination with categories I,II,III, denoting that alterations or additions would improve accuracy and/or completeness, which are outlined within the document*
IV	*No support found*

REVIEW OF PATHWAYS OF EFFECTS DIAGRAMS

GENERAL CONSIDERATIONS

The ways in which WUAs and related pressures impact fish and fish habitat have been the subject of much research, review, and synthesis to date. Canadian Science Advisory Secretariat (CSAS) processes have addressed various aspects, including four key endpoints - changes in habitat structure and cover, sediment concentrations, water temperature, and oxygen concentrations (DFO 2006), and subsequently, four DFO technical reports were produced focusing on changes in structure and cover (Smokorowski and Pratt 2007), temperature and oxygen (Mason and Metikosh 2007), water flow (Clarke et al. 2008), and suspended sediment (Robertson et al. 2006). Subsequently, DFO (2014) characterized the productivity-response curves to WUA effects on fish habitat, which included 12 different key endpoints – wetted area, sediments, structure/cover, nutrients, food supply, mortality, temperature, noise, electromagnetic fields, access to habitat, dissolved oxygen, and water flow.

It is important to recognize the balance between building comprehensive diagrams that integrate the complexity by which WUAs may impact fish and/or fish habitat, and those that are functional for their expressed purpose of FFHPP decision making and proponent communication. For example, the ‘Decrease in food supply’ endpoint is challenging to include comprehensively because a very large number of pressures may impact it, which would create an intractable level of complexity in the PoE diagrams. This is well illustrated in the Land-based PoE, where food supply may be affected by a loss of undercut banks, decrease in water quantity, decrease in water quality, decrease in organic structure, increase in water temperature, and decrease in baseflow. Further, there are complex interactions amongst various environmental factors, such as that between temperature and dissolved oxygen, which are not all addressed comprehensively for the sake of diagram tractability. We focused our suggested alterations around the above 12 endpoints, including the core ways in which WUAs and associated pressures impact fish and fish habitat, and in cases of inconsistencies amongst diagrams, we relied on the factors and terminology included in DFO (2014). In some cases, relevant factors such as dissolved oxygen, carbon dioxide, pH, and salinity, were assumed to be included under a generic pressure node ‘altered water quality’. In taking this approach, recognizing this balance of complexity, our review and proposed changes to draft PoE diagrams is not completely comprehensive of every way in which WUAs, pressures, and endpoints are potentially interconnected, but focus on core connectivity and diagram functionality. It is left to those that further develop and utilize these diagrams to interpret implicit complexities within general descriptive categories.

Although a focus on somewhat simplistic, tractable PoE diagrams is logical for this exercise, for many purposes it is also important to recognize the complex ways in which WUAs may impact fish, fish habitat, and ecosystems more generally. We did not comprehensively review whether all WUAs that are of relevance to FFHPP are included in the PoE diagrams, as this falls outside the scope of this exercise. However, it is worth noting that commercial shipping and its impacts are not currently included in the PoE diagrams as they were the subject of a separate CSAS process (DFO 2020a). Nor are any recreational activities such as boating and fishing, which fall outside of *Fisheries Act* regulatory reviews, but can have impacts on fish and fish habitat and are regulated. Last, we focused here on reviewing the validity and completeness of the PoE diagrams connecting pressures to endpoints, but do not address evidence relating endpoints to the ability to support fish and fish productivity.

LAND-BASED DIAGRAM

The proposed PoE diagram for land-based activities (***Figure 2***) includes WUAs: grading (e.g. development site, bank stabilization), excavating (e.g. new drains, trenches, ponds, pits), site preparation, stockpile management, land clearing, grubbing, site access, vegetation maintenance, vegetation clearing, cleaning and maintenance of structures, vegetation planting, and maintenance of industrial equipment (washing, refueling, servicing, storing).

As a general note on structure, the other PoE diagrams include sub-activities, which pressure pathways are further organized under, and this diagram does not, creating a lack of consistency. The stated WUAs are proposed to apply the following pressures:

1. Input of organic matter in water (e.g., fallen branches, trees, woody debris)

2. Altered groundwater flows to surface waters

3. Altered vegetation

4. Alteration of slopes and banks

5. Alteration of land drainage patterns

6. Introduction of oil, grease, fuel, herbicides, and other deleterious substances

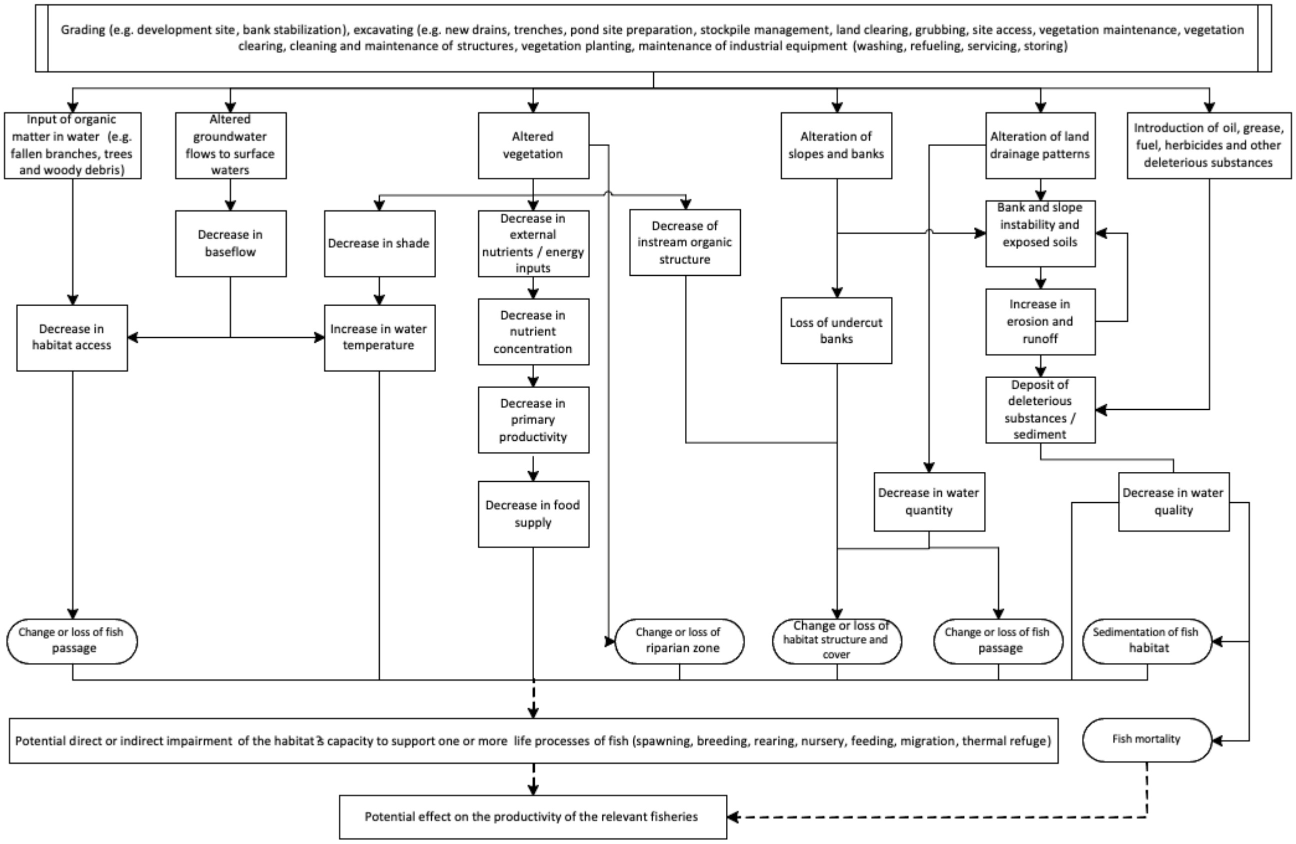


Figure 2: Draft (September 2020) pathways of effects diagram for land-based WUAs.

1. Input of organic matter in water (e.g., fallen branches, trees, woody debris)

Input of organic matter -> Decrease in habitat access -> Change or loss of fish passage *(III*)*

We considered habitat access under the definition of the ability of fish to occupy a habitat, which may be deterred by physical (e.g., passage, noise), chemical (e.g., deleterious substances), or biological (e.g., fear) factors. Although the introduction of vegetation (e.g., coarse woody materials or debris) from anthropogenic activities logically has potential to obstruct fish passage in stream ecosystems (Evans 1980), this phenomenon is not well documented in the literature. This may be partially because, through activities such as logging, major concurrent alterations occur to riparian vegetation, banks and slopes, and land drainage patterns, so loss of fish habitat is rarely attributed directly to input of organic matter such as woody materials. There is, however, more research on the impacts of beaver dams on fish passage, which is conceptually similar in that organic materials create a physical in-water obstruction (Lokteff et al. 2013; Bouwes et al. 2016). Lokteff et al. (2013) found that beaver dams present a partial obstruction to movement by numerous trout species, with passage success depending on an interaction between species and environmental characteristics such as water flow and the seasonal timing of migration. However, beaver dams also have recognized beneficial impacts on fish habitat (Bouwes et al. 2016). More broadly, vegetation, especially large woody material, plays many important beneficial roles in fish habitat, shaping river/stream morphology, creating flow refugia, providing structural cover for feeding as well as refuge from predators and water flows in rivers/streams, and structural habitat in lakes, reservoirs, estuaries, and coastal marine ecosystems as well (Angermeier and Karr 1984; Harmon et al. 1986; Murphy and Koski 1989; Everett and Ruiz 1993; Beechie and Sibley 1997; Thévenet and Statzner 1999; Smokorowski and Pratt 2007). Hence, the input of organic materials may have complex impacts on aquatic ecosystems and fish habitat, depending on the nature of the input and characteristics of the system. The fate of deposited large woody materials depends on complex water flow and material characteristics, which influences the rate at which wood materials form jams, and the temporal stability of jams (Abbe and Montgomery 1996) that structure aquatic habitats and potentially influence their role in fish habitat, including fish passage. Despite playing beneficial roles in aquatic systems through natural deposition processes, the input of vegetation into rivers may not be beneficial in less-natural circumstances (e.g., logging).

There is a theoretical basis to suggest that input of organic material (vegetation) due to WUAs can impact fish passage in streams, but it is not well supported with empirical data. As discussed above, input of organic material is an important natural process, but potential negative effects on fish passage may arise when WUAs result in increased input of woody material. Therefore, it would be more accurate and complete to alter ‘Input of organic matter in water’ to ‘Increased input of woody material’ for clarity [1]. In this case ‘woody material’ refers to trees, branches, and woody debris. As discussed above, the exact size and amount of woody debris that may cause a passage issue is not well studied or known. Upon entering the water, there are a range of potential issues covered in the in-water PoE diagram (e.g., smothering, alterations in water quality, change or loss of cover), hence, a connection may be added from ‘Increased input of wood material’ to ‘See in-water diagram’ [2]. Last, there is no logical connection between ‘Decrease in habitat access’ and ‘Change or loss of fish passage’ or ‘Increase in water temperature’. Alterations to in-water structure may have a variety of effects such as alterations in water temperature and changes to fish passage; however, these effects are covered in the In-water PoE diagram. Hence, the linkage between ‘Increased input of woody material’ and ‘Decrease in habitat access’ and ‘Change or loss of fish passage’ may be removed here [3], instead referring to the in-water PoE diagram [2] for more comprehensive coverage of its effects.

Input of organic matter -> Decrease in habitat access -> Increase in water temperature *(II*)*

Coarse woody materials play a complex role in aquatic ecosystems, particularly in streams and rivers, shaping geomorphology, flow and substrate distributions, water temperature and diverse aspects of the biological community (Angermeier and Karr 1984; Harmon et al. 1986; Heifetz et al. 1986; Murphy and Koski 1989; Fausch and Northcote 1992; Crispin et al. 1993; Gurnell et al. 1995; Beechie and Sibley 1997; Crook and Robertson 1999; Thévenet and Statzner 1999). Structure influences water flow patterns and in turn affects water temperatures in stream habitat (Hester et al. 2009; Majerova et al. 2015; Weber et al. 2017). However, as discussed above, these effects are covered comprehensively in the in-water PoE diagram, hence these connections could be removed [3].

2. Altered groundwater flows to surface waters

Altered groundwater flows to surface waters -> Decrease in baseflow -> Decrease in habitat access -> Change or loss of fish passage *(I)*

Groundwater influxes commonly play an important role in maintenance of the quantity and quality of fish habitat in streams and rivers due to their contribution to water flow (Blackport et al. 1995; Power et al. 1999; Fleckenstein et al. 2004; Chu et al. 2008; Perkin et al. 2017). Therefore, altering [reducing] groundwater flows into stream and river systems often results in a decrease in baseflow of river and stream ecosystems, which in turn results in lower water levels and a decrease in habitat access through change or loss of fish passage (Fleckenstein et al. 2004; Beatty et al. 2010).

Altered groundwater flows to surface waters -> Decrease in baseflow -> Increase in water temperature *(I*)*

Temperatures of groundwater flows are often more moderate than surface waters due to the buffering effect of the land mass from more rapid and extreme changes in environmental temperature above the surface. Therefore, seasonally, when water temperatures are relatively high in streams and river ecosystems, groundwater flows maintain colder water temperatures (Keery et al. 2007). This is particularly important in certain shallow stream ecosystems, which are kept relatively cool during the summer months, providing habitat for cold water species such as salmonids (Curry et al. 1994; Blackport et al. 1995; Power et al. 1999; Mason and Metikosh 2007; Chu et al. 2008; Waco and Taylor 2010; Rolls et al. 2012; Perkin et al. 2017). On the other extreme, during winter, groundwater flows are warm relative to ambient surface waters, and can be essential to maintaining overwintering pools (Cunjak 1996; Power et al. 1999; Mason and Metikosh 2007). Therefore, this pathway could be altered to address the dual role groundwater plays in maintaining water temperature and fish habitat, from the current ‘Increase in water temperature’, to ‘Altered water temperature’ [4].

Additional considerations

Decreases in baseflow also result in loss of wetted area, which means direct loss of fish habitat (Blackport et al. 1995; Cunjak 1996; Chu et al. 2008; Beatty et al. 2010). In some cases this may result in the loss of fish from a given area or system due to, for example, loss of overwintering pools (Cunjak 1996). Fish population productivity generally tends to decrease proportionally with declines in habitat area/quantity (Randall and Minns 2002; Minns et al. 2011) and fish diversity has also been demonstrated to decline with reduced water discharge (Xenopoulos and Lodge 2006). Therefore, ’Change or loss of wetted area’ may be added as another relevant endpoint [5]. Alterations in groundwater flow patterns typically result in decreased baseflow in lotic systems, but in some cases, it may result in increased baseflow to systems where the water is redirected. However, the most common issue occurs due to decrease in flow. Therefore, an asterisk* could be added to ‘Decrease in baseflow’, referring to a footnote that notes increases in baseflow, and their associated effects, are possible as well [6]. Additionally, there are a variety of impacts that changes in baseflow can have on fish habitat in addition to wetted area, that are related to substrate characteristics, structure, and water quality – a connection from ‘Altered groundwater flows to surface waters’ to ‘Altered water quantity’ directly to ‘Potential direct or indirect impairment of fish habitat’ may be warranted [7]. Groundwater also often plays a prominent important role in providing fish with food, and decreases in baseflow can result in reduced fish feeding opportunities and growth (Valiela et al. 1990; Weisberg and Burton 1993; Fujita et al. 2019). Therefore, a connection could be added between ‘Decrease in baseflow’ and ’Decrease in food supply [8].

3. Altered vegetation

Altered vegetation -> decrease in shade -> increase in water temperature *(I)*

Altered vegetation [decrease in riparian vegetation] commonly results in decreases in shade cover in stream ecosystems and the increased light penetration causes increased water temperatures (Barton et al. 1985; Theurer et al. 1985; Larson and Larson 1996; Garner et al. 2017), which in turn can affect fish habitat suitability (Broadmeadow et al. 2011). As ectotherms, fish are generally adapted to the natural thermal regime of their habitat, and are sensitive to changes in ambient water temperature due to its impact on their energetic needs and physiological performance (Eliason et al. 2011). Hence, altered vegetation [decrease in riparian vegetation] can be detrimental to fish when it causes water temperatures to increase beyond the optimal temperature ranges of affected fish species (Theurer et al. 1985; Mason and Metikosh 2007; Broadmeadow et al. 2011).

Altered vegetation -> decrease in external nutrients/energy inputs -> decrease in nutrient concentration -> decrease in primary productivity -> decrease in food supply *(I*)*

Riparian vegetation contributes external (allochthonous) nutrients that form an important component of primary productivity of food webs that support fish (Tabacchi et al. 1998; Pusey and Arthington 2003; Tank et al. 2010). From this perspective, this pathway is supported. However, removal of vegetation from the riparian zone impacts aquatic ecosystems in complex ways depending on the adjacent land use and geological characteristics of the region. For example, in regions with a deep soil layer, after loss of riparian vegetation, continuous erosion of banks leads to higher suspended sediment and nutrient inputs into stream ecosystems (Laubel et al. 2003; Robertson et al. 2006; Taylor and Owens 2009; Chapman et al. 2014). The effects are also important in coastal marine habitats as well (Valiela and Cole 2002; Gedan et al. 2011; Quiros et al. 2017). The exact nature of how bank erosion occurs and impacts aquatic conditions depends on the complex interplay between water flow characteristics and the geological conditions of the watershed (Fox and Wilson 2010). Further, the replacement of riparian vegetation with land use such as agriculture increases nutrient inputs, which is also problematic for fish communities (Wichert and Rapport 1998). Hence, depending on the context, altered vegetation could decrease or increase the amount of nutrients and primary productivity, which are both generally detrimental to fish communities. 'Decrease in external nutrients/energy inputs' could be changed to 'Altered external nutrients/energy inputs' [9]. To simplify the diagram, ‘Decrease in nutrient concentration’ is redundant with the above node and could be removed [10]. Consistent with change [9], 'Decrease in primary productivity' may be changed to 'Altered primary productivity’ to be comprehensive [11]. Further, riparian vegetation is a source of not only nutrients supporting the base of the food web, but also a direct source of fish food (e.g., terrestrial insects; Davies and Nelson 1994; Pusey and Arthington 2003), therefore ‘Altered vegetation’ could be connected to ‘Decrease in food supply’ [12].

Altered vegetation -> **decrease of instream organic structure** -> **change or loss of habitat structure and cover *(I*)***

Riparian vegetation plays a vital role in providing instream organic structural fish habitat (Heifetz et al. 1986; Murphy and Koski 1989; Fausch and Northcote 1992; Crook and Robertson 1999; Pusey and Arthington 2003; Smokorowski and Pratt 2007). This is particularly salient with smaller rivers and streams where the land-water interface plays a major role in ecosystem structure and function. However, organic structure plays a role in fish habitat in many types of aquatic ecosystems (Smokorowski and Pratt 2007; Sass et al. 2019), not just 'instream', therefore the wording could be changed to 'aquatic' [13].

Altered vegetation -> change or loss of riparian zone *(I*)*

Vegetation is generally an integral component of the riparian zone, and hence, alteration [removal] of vegetation from the riparian zone could be considered direct change or loss of the riparian zone. This often has subsequent effects to the riparian zone, as vegetation plays a role in stabilizing sediments (Barton et al. 1985), which often erode away after riparian vegetation removal, changing the geomorphology of the aquatic ecosystem and the conditions and location of the riparian zone (Tabacchi et al. 1998, 2000; Laubel et al. 2003). See DFO (2021) for definitions of riparian zones in freshwater and marine habitats. Riparian vegetation also plays an essential role in river geomorphology including bank stability and maintenance of undercut banks (Abernethy and Rutherfurd 1998; Tabacchi et al. 1998, 2000; Myers and Resh 2000; Laubel et al. 2003). In some cases riparian loss leads to channel incision, which has negative effects on habitat conditions and fish communities (Shields et al. 1994). Therefore, to cover the effects of riparian vegetation loss comprehensively, an additional connection from 'Altered vegetation' to 'Bank and slope instability and exposed soils' could be added [14]. As discussed above, vegetation also plays a key role in habitat structure and cover, and therefore a connection may be warranted from 'Altered vegetation' to 'Change or loss of habitat structure and cover' [15].

Alteration of slopes and banks -> **Loss of undercut banks** -> **Change or loss of habitat structure and cover *(I*)***

Undercut banks represent important fish habitats, providing structure and cover, as well as supporting food supply (Myers and Resh 2000). They are formed as the roots of riparian vegetation retain soils while water flows erode the soil underneath over years to decades. Altering [aquatic ecosystem shoreline] slopes and banks typically involves removing riparian vegetation, which removes its ability to maintain bank structure including undercut banks (Heifetz et al. 1986; Tabacchi et al. 1998, 2000; Myers and Resh 2000; Laubel et al. 2003). Therefore, upon altering banks, it is challenging to re-establish undercut banks in a timely manner due to the need for long-term hydrological processes for formation. Noting the importance of undercut banks, the effects of slopes and banks more generally are included in the diagram, and the inclusion of this specific bank type is a level of detail that is not included for other components of these diagrams, hence, 'loss of undercut banks' could be removed as a node [16], and the linkage would be direct from 'Alteration of slopes and banks' to 'Change or loss of habitat structure and cover'.

4. Alteration of slopes and banks

Alteration of slopes and banks -> **Bank and slope instability and exposed soils** <-> **increase in erosion and runoff** -> **deposit of deleterious substances** -> **decrease in water quality** -> **sedimentation of fish habitat *(I)***

Altering [aquatic ecosystem shoreline] slopes and banks commonly results in bank instability (especially due to removal of riparian vegetation) and exposure of soils, which in turn causes increases in erosion and runoff into aquatic ecosystems (Tabacchi et al. 1998; Wynn et al. 2004; Robertson et al. 2006; Fox and Wilson 2010; Chapman et al. 2014; Krzeminska et al. 2019). Deleterious substances are defined in the *Fisheries Act* as “any substance that, if added to any water would degrade or alter the water quality such that it could directly or indirectly harm fish, fish habitat, or the use of fish by humans”. Suspended sediments degrade water quality and could be considered a deleterious substance themselves, and also often contain a variety of deleterious substances such as mercury (Wang et al. 2004; Robertson et al. 2006), and excessive nutrient concentrations as well (Cloern 2001; Hauxwell et al. 2003; Deegan et al. 2012). Rates of contaminant deposition may be particularly high in areas where activities such as mining have historically deposited high levels of contaminants (Stone 2000). Suspended sediments can ultimately settle into the benthos, resulting in sedimentation of fish habitat, which reduces habitat heterogeneity including a loss of interstitial spaces that provide key structural complexity (Robertson et al. 2006; Kemp et al. 2011; Chapman et al. 2014).

Alteration of slopes and banks -> **Bank and slope instability and exposed soils** <-> **increase in erosion and runoff** -> **deposit of deleterious substances** -> **decrease in water quality** -> **fish mortality** ***(I*)***

The liberation of bank soils leads to a wide variety of potential impacts on the conditions of aquatic ecosystems that can lead to fish mortality through direct impairment of fish physiological function by decreasing access to oxygen, or reducing visibility, impairing a fish’s ability to navigate, capture prey, or avoid predators (Robertson et al. 2006; Chapman et al. 2014). Soils often contain deposited harmful chemical contaminants as well, which have an array of direct negative effects on fish including mortality (Taylor and Owens 2009). However, impairment of fish population productivity can occur from sub-lethal impacts as well, for example, the energetic costs of environmental stressors resulting in reduced growth and reproductive output (Lévesque and Dubé 2007; Schreck 2009). Therefore, the ‘Fish mortality’ endpoint could be altered to ‘Sublethal effects and/or mortality’ [17]. Here we define sublethal effects as physical, physiological, or behavioural alterations caused by anthropogenic activities that may result in reduced biological fitness of individuals, which in turn reduces population (fisheries) productivity.

5. Alteration of land drainage patterns

Alteration of land drainage patterns -> **Bank and slope instability and exposed soils** <-> **increase in erosion and runoff** -> **deposit of deleterious substances** -> **decrease in water quality** -> **sedimentation of fish habitat** ***(I*)***

Alteration of land drainage patterns often causes changes in riparian erosion patterns, which leads to increases in erosion and runoff (Likens and Bormann 1974; Blann et al. 2009; Vlotman et al. 2020). This pressure pathway is otherwise similar to that discussed above in relation to alteration of slopes and banks and is well-supported. Notably, the sedimentation of fish habitat may cause direct fish mortality by depriving eggs or larvae of oxygen (Newcombe and Jensen 1996; Wright and Hopky 1998; Kemp et al. 2011; Chapman et al. 2014), so a connection from ‘Sedimentation of fish habitat’ to ‘Sublethal effects and/or mortality' may be added [18].

Alteration of land drainage patterns -> Decrease in water quantity ***(I*)***

Altering the drainage patterns of water from land into aquatic ecosystems often causes reduced water quantity in the systems which water is diverted from, which reduces the amount of wetted area, i.e., fish habitat (Likens and Bormann 1974; Blann et al. 2009; Minns et al. 2011; Vlotman et al. 2020). This is especially problematic in smaller aquatic ecosystems such as small rivers and streams, which rely on surface runoff for water supply. Further, the habitats to where the water is diverted can also experience changes in habitat quantity and quality. For example, diversion of water in the Ganges River resulted in substantial changes in conditions of coastal estuaries where freshwater was diverted, including altered biological communities and reduced fish productivity (Monirul Qader Mirza 2006). Altering drainage patterns by changing permeability of land (i.e., hardening, urbanization) can also lead to an increase flashiness of flows, or a frequent temporary increase in water quantity that can lead to reduced biotic diversity via losses of intolerant species (Baker et al. 2004; Walsh et al. 2005). Therefore, water quantity may decrease and/or increase, both of which can be problematic. Therefore, 'Decrease in water quantity' could be changed to 'Altered water quantity' for comprehensiveness [19]. This alteration in water quantity is directly connected to wetted area (with its own specific effects; DFO, 2014); therefore, a connection from 'Alteration in water quantity' to 'Change or loss of wetted area' may be added [20]. Further, a decrease in water quantity connects to various issues outlined in the Flows PoE diagram, hence a connection may be added from 'Altered water quantity' to 'see Flow PoE diagram' [21].

Additional considerations

A combination of the land-based pressures (altered vegetation, altered slopes and banks, altered land drainage patterns) may also contribute to additional pressure pathways/endpoints including facilitating invasive species pathways (Hobbs 2000; Havel et al. 2015) [22] . This same combination of pressures may also enable greater access to the waterbody, which can result in increased fishing pressure. However, recreational fisheries are not managed directly by DFO. Therefore, an additional endpoint may be added connecting these pressures to 'Increased human access', connecting to 'Consult with relevant management agency(ies) [23].

Alteration of land use that includes impervious surfaces such as asphalt can also cause thermal loading in aquatic ecosystems as well (Herb et al. 2008), which may warrant a connection from alteration of land drainage patterns to 'Altered water temperature' [24]. Notably, many of the negative impacts of near-water construction projects can be mitigated in some cases with best management practices (Houser and Pruess 2009).

6. Introduction of oil, grease, fuel, herbicides, and other deleterious substances

Introduction of deleterious substances -> **deposit of deleterious substances** -> **decrease in water quality** -> **sedimentation of fish habitat** ***(I*)***

Numerous human activities cause the introduction of deleterious substances into aquatic ecosystems; these substances are hazardous to fish health (Niimi 1983; Adams et al. 1996; Collier et al. 2013; Solomon et al. 2013; Araújo et al. 2018), which in turn can reduce the productivity of populations and the structure and stability of biological communities (McKinley and Johnston 2010). In the context of using machinery on land near water, the protection of freshwater resources in Canada requires that proponents ensure that equipment and machinery are in good operating condition, free of leaks, excess oil and grease, and serviced/fueled at a distance from a watercourse or waterbody (e.g., >30 meters; British Columbia's *Water Act, 1996*). The sources and types of deleterious substances are vast, ranging from point sources of chemicals such as polycyclic aromatic hydrocarbons from spilled oil or gasoline (Armon and Starosvetsky 2015; Nowak et al. 2019), to large scale herbicide use in agriculture (Solomon et al. 2013) or heavy metal leaching from mining (Banks et al. 1997; Intamat et al. 2016). The effects of contamination are truly diverse, for example, herbicides have been documented to form chemical barriers to fish population connectivity (Araújo et al. 2018). This pathway is connected to sedimentation of fish habitat; as contaminants typically settle into sediments, they could be considered an integral component. Further, sediment itself could be considered a deleterious substance in some cases under the *Fisheries Act* definition, and its impact on fish and fish habitat is discussed and supported above.

Introduction of deleterious substances -> **deposit of deleterious substances** -> **decrease in water quality** -> **Fish mortality** ***(I)***

There are many cases in which introduction/deposit of deleterious substances can cause direct fish mortality, depending on the toxicity and concentration of the substance (Niimi 1983; Adams et al. 1996; Collier et al. 2013; Solomon et al. 2013; Chapman et al. 2014; Araújo et al. 2018), or its impact on other habitat features such as water temperature, oxygen concentration, or water turbidity (Robertson et al. 2006; Chapman et al. 2014). This is a complex topic that will not be covered extensively here, but the degree to which a deleterious substance will cause fish mortality (as well as sublethal effects that influence biological fitness, in turn influencing population size) will depend on the vulnerability of the species and life stage and the toxicity and concentration of the substance. Overall this is a well-supported pathway; however, it would be more encompassing of the range of biological control chemicals commonly applied to rename the top pressure node changing 'herbicide' to 'pesticide', resulting in the node title 'Introduction of oil, grease, fuel, pesticides, and other deleterious substances' [25]. Further, the introduction of these substances impacts water quality directly, independent of deposition; hence a connection could be added directly from 'Introduction of oil, grease, fuel, pesticides and other deleterious substances' to 'Decrease in water quality' [26].

Potential alterations to the land-based PoE diagram

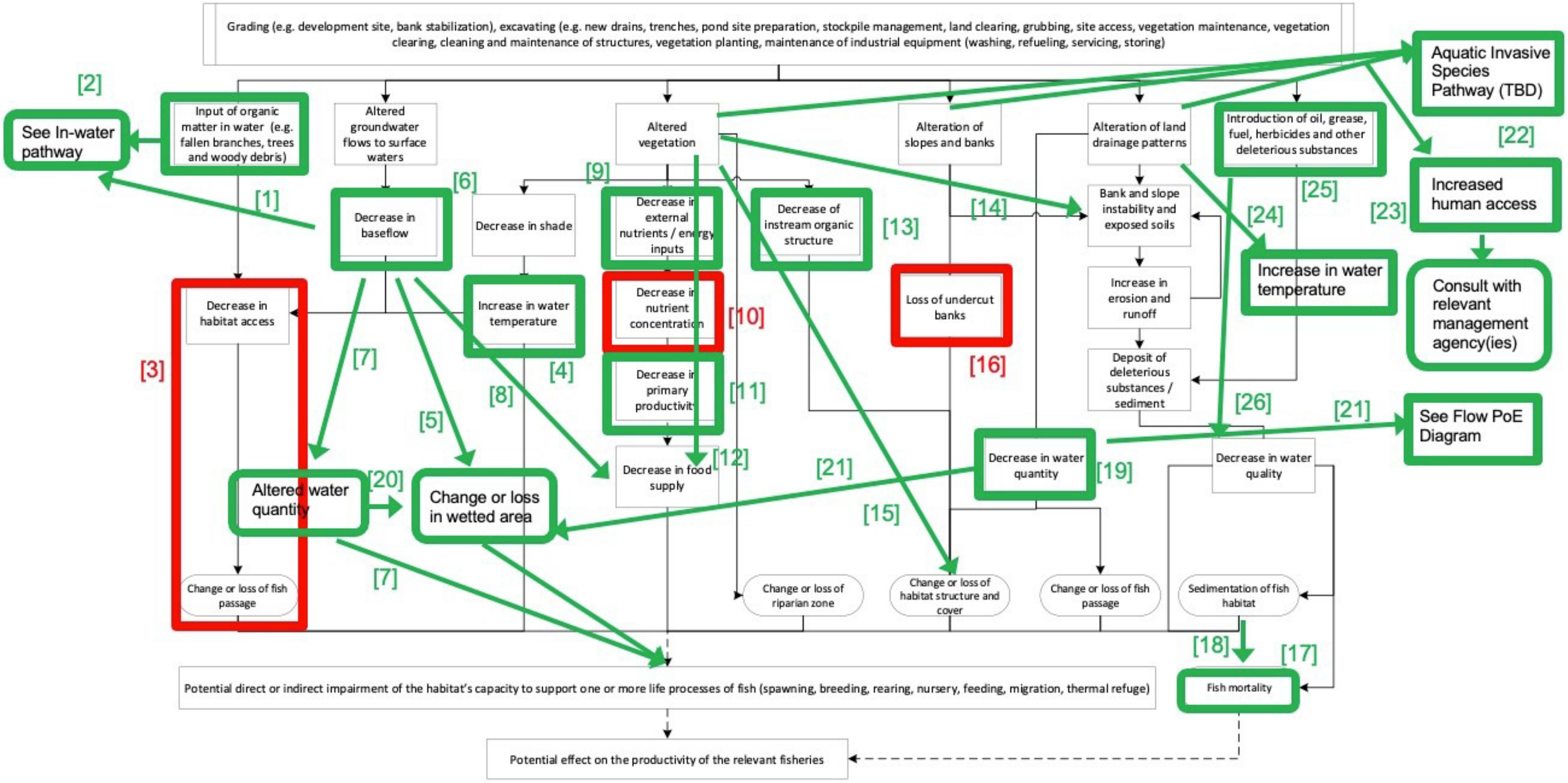


Figure 3: Overview of potential alterations to the draft (September 2020) Pathways of Effects diagram for land-based WUAs. Additional lines indicate connections that may be added (green) or removed (red); additional boxes indicate alterations or additions to pressures or endpoints.

NOISE AND ENERGY DIAGRAM

The proposed PoE diagram for Noise and Energy producing WUAs (***Figure 4***) including: use of explosives, seismic surveys, pile driving, drilling, vibratory drilling, and other.

These WUAs are proposed to apply the following pressures:

1. Detonation in or near water

2. Introduction of underwater noise

3. Release of compressed air

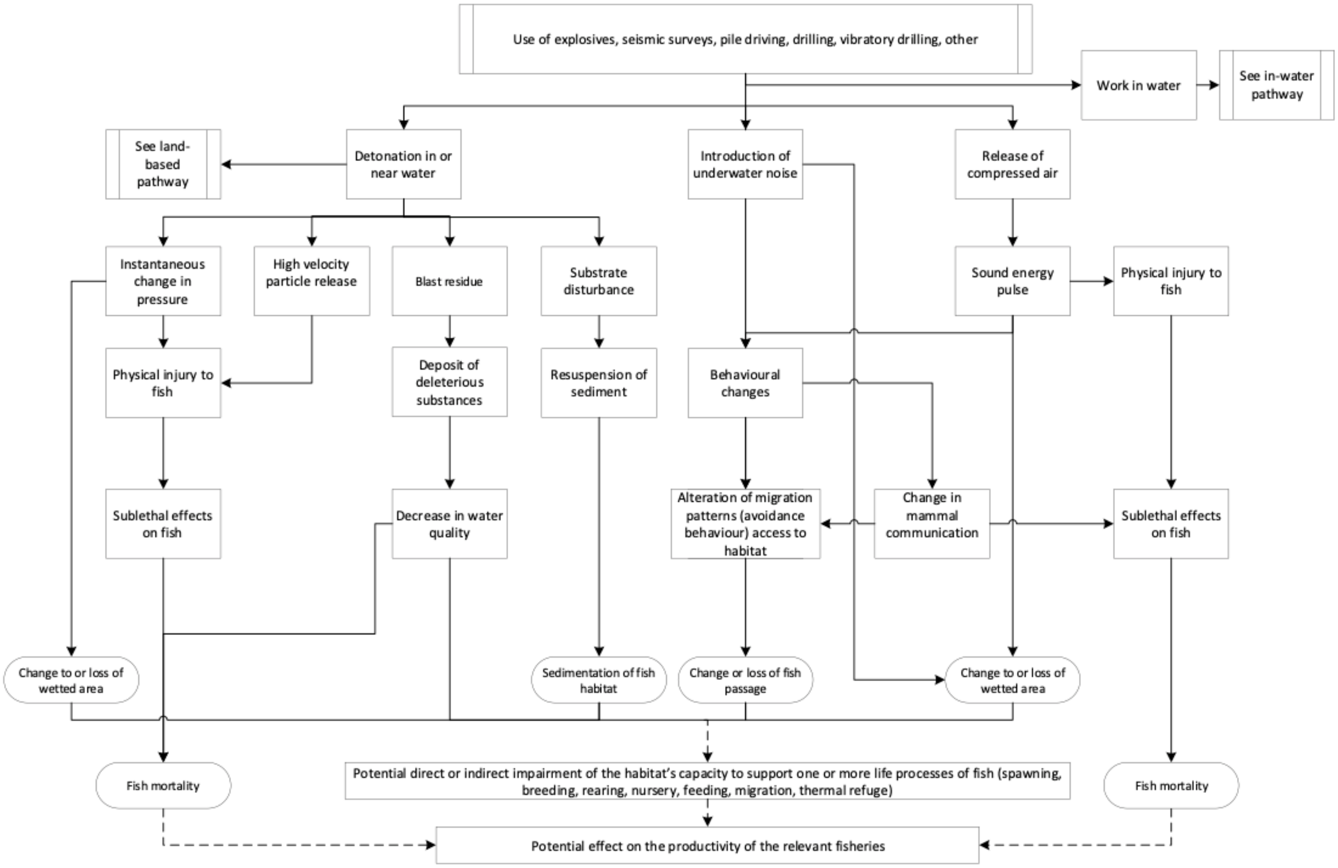


Figure 4: Draft (September 2020) Pathways of Effects diagram for noise and energy producing WUAs

1. Detonation in or near water

Detonation in or near water -> Instantaneous change in pressure -> Change or loss of wetted area *(IV)*

There is little evidence available to support that pressure changes associated with detonation activities in or near water result in significant losses of wetted area, and therefore, 'Change or loss of wetted area' may be removed [1].

Detonation in or near water -> Instantaneous change in pressure -> physical injury to fish -> Sublethal effects on fish -> fish mortality *(I*)*

In the case of the detonation of an explosive in or near water, there is the creation of a shock/detonation wave that results from the chemical reactions that convert unstable compounds into stable compounds and releases heat and gases. The explosive release of the gas causes a very fast increase in pressure in the surrounding area of the explosion, and that creates a pressure wave that propagates away from the point of the explosion at very high speeds (several thousand metres per second) but is also limited in its extension based on the amount chemical reaction that took place initially.The rapid changes in pressure associated with blasting activities in or near water are well documented to cause physical injuries and mortality in fish and marine mammals (Teleki and Chamberlain 1978; Dalen and Knutsen 1987; Wright and Hopky 1998; Gordon et al. 2003; Weilgart 2007; Dahl et al. 2020). The general guideline in Canada is to avoid overpressure of 100 kPa to minimize the likelihood of significant negative effects (Wright and Hopky 1998). The extent to which blasting activities may result in excessive overpressure depends on a variety of factors related to the distance of the blasting activity from fish habitat and physical characteristics of the habitat (Keevin 1998; Wright and Hopky 1998). Physical injuries can occur to all life stages of fish, with eggs being highly vulnerable (Dalen and Knutsen 1987; Faulkner 2006; Faulkner et al. 2008; Govoni et al. 2008; Dahl et al. 2020). Both sublethal and lethal impacts are possible depending on the level of exposure and tolerance of the species, which consistent with suggestions for other PoE diagrams, could be included as an inclusive ‘Sublethal effects and/or mortality’ endpoint [2]. Further, in addition to physical injuries, fish may also experience physiological stress in response to detonation effects, and this node could be altered from ‘physical injury’ to ‘Physical injury and/or stress to fish’ [3]. We considered ‘Physical injury and/or stress to fish’ to include any external or internal injury and physiological stress in diverse aquatic organisms, including other vertebrates and invertebrates. In addition to physical injury, stress, and mortality, in some cases fish and marine mammals may become exposed to pressure changes and/or noise at a greater distance than the maximum extension of the shock wave, which can result in behavioural avoidance of the affected area (Nowacek et al. 2007; Popper and Hawkins 2019). This can cause exclusion of these animals from their habitats, and hence, a connection could be added from ‘Instantaneous change in pressure’ to a new pressure node ‘Altered migration patterns (avoidance behaviour) access to habitat’ [4].

Detonation in or near water -> High velocity particle release -> physical injury to fish -> sublethal effects on fish -> fish mortality *(I*)*

Within a radius around detonations, large particles (e.g., rocks) traveling at high velocity could potentially cause fish injury and mortality; however, there is little direct documentation of this. Water exerts high drag on moving objects relative to air and the range that particles travel at high velocity may be small, especially relative to the radius in which the blast shock wave and associated pressure gradient would cause injury and mortality to fish, as discussed above. In addition to changes in pressure, detonations also cause particle motion, the other major component of sound (Nedelec et al. 2016; Hawkins and Popper 2017). This can result in intense substrate vibrations that can cause fish injury and mortality, especially to fish eggs located in the substrate (Faulkner 2006; Faulkner et al. 2008). This is measured in peak particle velocity of the substrate; general guidelines in Canada suggest that peak particle velocity above 13 mm/s are more likely to cause physical injury and mortality (Wright and Hopky 1998). Injuries and mortality in fish and mammals associated with detonations tend to be attributed more often to pressure waves than particle motion in studies, discussed above. No reference to ‘high velocity particle release’ was found, therefore this node may be more accurately named ‘high velocity water and solid particle movement’ [5]. There is generally less research on the effects of particle motion on fish and fish habitat compared to the effects of rapid pressure changes and, more broadly, sound energy. Movement of the sound pressure wave caused by the energy transfer between moving water molecules can cause both physical and auditory injury to middle and inner ear and risk is correlated with the distance of the receiver from the source. Auditory injury to mammals causes temporary and permanent noise frequency specific hearing loss. Both mechanisms can increase mortality due to loss of foraging ability or increased predation risk and loss of orientation capabilities. The movement of solids is directly associated with alterations in the structure of fish habitat, and hence, a connection could be added from ‘High velocity water and solid particle movement’ to ‘Change or loss of habitat structure and cover’ [6] (added as a new endpoint to this PoE diagram).

Detonation in or near water -> Blast residue -> Deposit of deleterious substances -> Decrease in water quality *(II*)*

By-products of explosive detonation activities can include deleterious substances like ammonia that are harmful to fish (Wright and Hopky 1998). Further, blasting often disturbs sediments, which can release deleterious substances contained within, such as heavy metals (Bach et al. 2017). Hence, a connection from ‘Resuspension of sediment’ to 'Deposit of deleterious substances’ may be added [7]. Both deleterious substances and sediment associated with detonations have been linked to sublethal impacts on fish (Nielsen et al. 2015; Bach et al. 2017), although there is little evidence linking blast residue directly with fish mortality, despite a strong theoretical basis.

Detonation in or near water -> Substrate disturbance -> resuspension of sediment -> sedimentation of fish habitat *(I*)*

Detonation in or near water has been documented to cause substrate disturbance and resuspension of sediment and hence sedimentation of fish habitat (Wright and Hopky 1998; Klemperer and Cash 2007; Girma et al. 2012; Nielsen et al. 2015). Notably, the sedimentation of fish habitat may cause direct fish mortality by depriving eggs or larvae of oxygen (Newcombe and Jensen 1996; Wright and Hopky 1998; Robertson et al. 2006; Kemp et al. 2011; Chapman et al. 2014) and may also have sublethal effects on fish (Chiasson 1993), which may warrant an additional connection from ‘Sedimentation of fish habitat’ to 'Sublethal effects and/or mortality' [8]. Sedimentation also directly affects habitat structure, and hence, a connection could be added from ‘Substrate disturbance’ to ‘Change or loss of habitat structure and cover’ [9].

Additional considerations

The detonation of explosives is also a source of underwater sound, which has a similar set of effects on aquatic organisms as other high intensity sound sources (e.g., impact pile driving and seismic exploration), including physical injury, physiological stress, and behavioral avoidance and impairment (Popper and Hawkins 2019; Dahl et al. 2020). This represents impulsive sound (DFO (2021); Martin et al. 2020), and therefore ‘Sound energy pulse’ would be more accurately named ‘Impulsive sound’ [10], with a connection added from ‘Detonation in or near water’ to ‘Impulsive sound’ [11].

2. Introduction of underwater noise

Introduction of underwater noise -> Behavioral changes -> Alteration of migration patterns (avoidance behaviour) access to habitat -> change or loss of fish passage *(II*)*

Numerous WUAs result in the introduction of underwater noise, such as seismic surveys, wind farms, drilling, acoustic profilers, or ships/motor boats (Nowacek et al. 2007; Slabbekoorn et al. 2010; Maxwell et al. 2018; Popper and Hawkins 2019; Dahl et al. 2020; MacLean et al. 2020; Popper et al. 2020). There is a wide range of well documented impacts of underwater noise on fish and marine mammal behavior (Nowacek et al. 2007; Popper and Hastings 2009; Mueller-Blenkle et al. 2010). In some situations noise is produced specifically to alter the behavior of cetaceans or fishes, to deter them from fishing gear, dams, or specifically to deter passage (Nowacek et al. 2007; Putland and Mensinger 2019). Therefore, noise can certainly alter fish passage, although no specific documentation of this was found specifically in relation to WUAs. Noise can have substantial effects on mammal behavior, such as altered directional heading and surfacing frequency (McCauley et al. 2000), alterations of migration routes and exclusion from important habitat (Nowacek et al. 2007; Weilgart 2007). Therefore, the 'Change or loss of fish passage' node could be removed [12], making a direct connection between ‘Alteration of migration patterns (avoidance behavior)/ access to habitat’ to ‘Potential direct or indirect impairment…’.

Noise may take the form of either impulsive sounds (high intensity, abrupt, short duration noise from sources such as detonations or air guns), or continuous sounds (occur continuously for longer periods of time, from sources such as shipping or drilling; see DFO (2021)for definitions). Therefore, ‘Introduction of underwater noise’ may be altered to ‘Release of acoustic energy in water (sound)’ [13]. This connects to ‘Continuous sound’, which subsequently connects to ‘Behavioural changes’ [14]. At close distances, these continuous sounds may also cause physical injury or stress to fishes or marine mammals, which warrants a connection from ‘Continuous sound’ to ‘Physical injury and/or stress to fish’ [15]. The altered ‘Impulsive sound’ [12] would also fit as a subsidiary of the ‘Release of acoustic energy in water (sound)’ node [16], and subsequently follow the same pathways as ‘Continuous sound’ thereafter as outlined on the original draft diagram.

The behavioral effects of noise are relevant to a wide variety of contexts, including fish migration irrespective of whether fish passage is involved, navigation in movement contexts outside of traditional definitions of migration, as well as other fitness related processes, such as feeding, predator avoidance, or larval development (Popper and Hastings 2009; Slabbekoorn et al. 2010; Stanley et al. 2012; Popper and Hawkins 2019; Di Franco et al. 2020; Popper et al. 2020). Hence, this pathway could be altered to include a direct link between ‘Behavioral changes’ to ‘Sublethal effects and/or mortality’ [17]. Further, anthropogenic noise can also cause physical injury and physiological stress responses in fish and marine mammals (McCauley et al. 2003; Nowacek et al. 2007; Popper and Hastings 2009; Slabbekoorn et al. 2010; De Soto et al. 2013; Sierra-Flores et al. 2015). For example, even boat motor noise exposure has potential to have physiological effects that translate into sublethal impacts and fish mortality (Simpson et al. 2016; Fakan and McCormick 2019).

There is some guidance available on the international standards for noise pollution in oceans (McCarthy 2007), as well as mitigating the effects of seismic survey activities in Canada, including a 500 meter impact zone surrounding the sound source (DFO 2020b).

Introduction of underwater noise -> Behavioral changes -> Change in mammal communication -> Alteration of migration patterns (avoidance behaviour) access to habitat -> Change or loss of fish passage *(III*)*

There is a strong basis of support that underwater noise impacts marine mammal communication (Nowacek et al. 2007; Parks et al. 2016; Fournet et al. 2018), which is important for coordinated migratory movements (Crane and Lashkari 1996; Nowacek et al. 2007). Noise has also been documented to affect movement patterns during migration (Nowacek et al. 2007; Weilgart 2007). There is also evidence that noise can interfere with the reception of echolocation clicks produced by porpoises and other odontocetes during foraging (Gervaise et al. 2012; Clausen et al. 2018). There is a strong theoretical basis for this pathway, although there is not extensive evidence on this connection explicitly. There is a terminological inconsistency with connecting a node on mammal communication with changes to fish passage (and sublethal effects on fish, fish mortality below). Importantly, underwater noise can affect the communication and navigation abilities of a wide variety of marine life, including fish and invertebrates (Radford et al. 2014; de Soto 2016). Hence, ‘Change in mammal communication’ could be altered to more generic terminology such as ‘Impaired communication and ability to navigate’ [18]. Impaired communication is defined here as a reduction in the capacity of aquatic organisms to exchange information. It is important to recognize a key mechanism in altered/impaired communication, which occurs through acoustic masking (see DFO (2021), especially with continuous sounds that have a sustained impact (Clark et al. 2009). Therefore, 'Acoustic masking' could be added to connect 'Continuous sound' with 'Altered communication' [19]. This same effect also occurs with impulsive sounds for the relatively shorter period when the sound is being produced, hence 'Impulsive sound' could also be connected to 'Acoustic masking' [20]. Overall, it is important to recognize that both impulsive and continuous sound can have a range of similar impacts, but impulsive sounds are more likely to cause acute injury at greater distance from the source than continuous sound sources, while continuous sounds are more likely to impair communication and cause behavioural exclusion from key habitats due to their pervasiveness in aquatic habitats.

Introduction of underwater noise -> Behavioral changes -> Change in mammal communication -> Sublethal effects on fish -> Fish mortality *(III*)*

As discussed above, this pathway is well supported, but the sublethal effects on fish extend beyond behavior and mammal communication, including physiological stress and injury and impacting a variety of organisms. Related changes are suggested above.

Introduction of underwater noise -> Change or loss of wetted area *(IV)*

Similar to changes in pressure above, there is little scientific evidence available to support that underwater noise causes a change or loss of wetted area, but for the period noise is being produced it may result in reduced habitat access by mobile aquatic organisms through deterrence, or because orientation is disrupted (Montgomery et al. 2006). Therefore 'Change or loss of wetted area' may be removed [21].

3. Release of compressed air

Seismic surveys commonly use air guns, which release compressed air to produce sound waves (DFO 2020b). This is a common and highly studied component of underwater noise (Dalen and Knutsen 1987; Gordon et al. 2003; Løkkeborg et al. 2012; Carroll et al. 2017; DFO 2020b), with specific guidelines in Canada (DFO 2020b), which are currently under review. As a major component of underwater noise, the impacts of noise from seismic air guns and the completeness of these pathways are covered above in relation to the 'Introduction of underwater noise' pressure pathway. As one of many sources of anthropogenic noise, there may not be a need to include this specific pressure in addition to the general 'Introduction of underwater noise' pressure [22].

Additional Considerations

Underwater power cables are commonly installed along the bottom/floor of aquatic ecosystems to transport electricity for human use, and the number of these cables is likely to continue to accelerate with increased focus on offshore wind energy projects (Tricas and Gill. 2011; Causon and Gill 2018; Taormina et al. 2018). Cable installation and removal can generate impacts covered in placement and removal of materials, discussed in the In-water diagram below. Cables may be installed above, on, or buried within substrates (Causon and Gill 2018; Taormina et al. 2018), which would have an influence on their physical impacts on fish habitat. Additional potential impacts specific to power cables include generation of heat, toxic chemicals such as chlorine and bromide through electrolysis, and electromagnetic fields (EMFs) (Taormina et al. 2018). Both heat and toxic chemicals generally impact a localized area around the cables, depend on cable types and installation conditions, and can to a large extent be mitigated with specific practices, including modern cable design and insulation (Tricas and Gill. 2011; Taormina et al. 2018). These are important considerations for managing electrical cable installation projects, and the impacts are covered in the existing pathways with connections in the In-water diagram between ‘Placement of materials’ and ‘Altered water quality’ and ‘Altered water temperature’, discussed below.

The impacts of EMFs from power cables on aquatic organisms are of particular concern (DFO 2014). Cables commonly generate EMFs within proximity to the cables, including magnetic fields and, in seawater, induced electric fields. Affected areas are variable from 5-20 meters surrounding cables depending on cable voltage, current type (alternating or direct current), and installation style (e.g., above or underground, insulated or not). In a synthesis, Tricas and Gill (2011) reported these ranges with peak magnetic fields of 160 µT and peak induced electric fields of 7.65E^{-04}. Tricas and Gill (2011) also provide a synthesis of aquatic organisms that may be affected by these currents due to their abilties to sense magnetic and/or electric fields for use in navigation and/or foraging, which includes a range of fishes, sharks, turtles, marine mammals, and invertebrates. Of particular concern is that EMFs will cause sensitive species to become attracted, deterred, or disoriented due to these produced fields, impacting their feeding or migration success (Westerberg and Lagenfelt 2008; Gill and Bartlett 2010; Tricas and Gill. 2011; Hutchison et al. 2020), or if organisms spend extended periods of time in close proximity to cables, they may have direct negative effects on health (Öhman et al. 2007). Despite the examples referenced above (and references therein), there is generally a lack of strong evidence to support the prevalence or degree of these impacts with comprehensive, robust studies in natural ecosystems. The impacts of EMFs are restricted to relatively small regions (<20 meters) surrounding power cables, and there are likely situations where these impacts may be more prevalent, such as with benthic-oriented species, or if cables are placed within a constricted area along a migration route for a species that is sensitive to EMF (e.g., American eel; *Anguilla rostrata*). Much more research is needed to understand the prevalence and degree of impacts and the ecological factors that determine them. There is, however, sufficient evidence to include EMFs in this diagram, connecting WUAs -> ‘Electromagnetic field production’ -> ‘Alteration of migration patterns/access to habitat’ -> ‘Sublethal effects and/or mortality’ [23]. There is also potential for direct impacts of EMF on fish health, therefore ‘Electromagnetic field production’ may be connected directly to ‘Sublethal effects and/or mortality’ as well.

Overview of potential alterations to the noise and energy PoE diagram

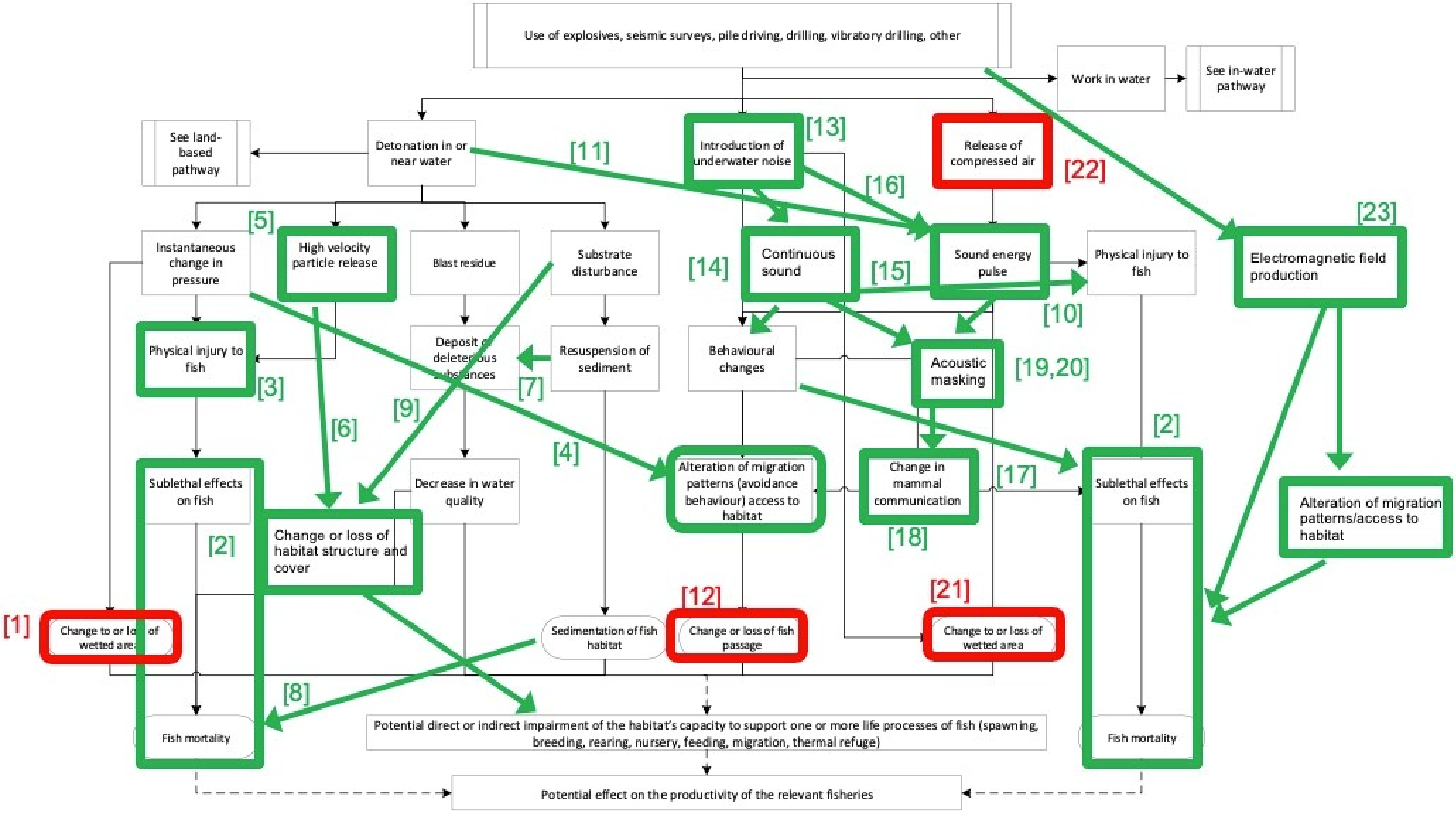


Figure 5: Overview of potential alterations to the draft (September 2020) Pathways of Effects diagram for noise and energy producing WUAs. Additional lines indicate connections that may be added (green) or removed (red); additional boxes indicate alterations or additions to pressures or endpoints

IN-WATER DIAGRAM

The proposed PoE diagram for in-water WUAs (***Figure 6***) include: dredging, spoil disposal, placement of materials and structures in water, aquatic vegetation removal, structural removal, channel excavation, use of manual and industrial equipment in water, organic debris removal, log salvage, culvert maintenance, water course crossings, and maintenance of industrial equipment (washing, refueling, servicing, storing).

These WUAs are proposed to apply the following pressures or sub-activities:

1. Use of machinery in water

2. Removal of materials (including organics)/structures

3. Placement of materials/structures in water

4. Removal of aquatic vegetation

5. Smothering of bed/seafloor

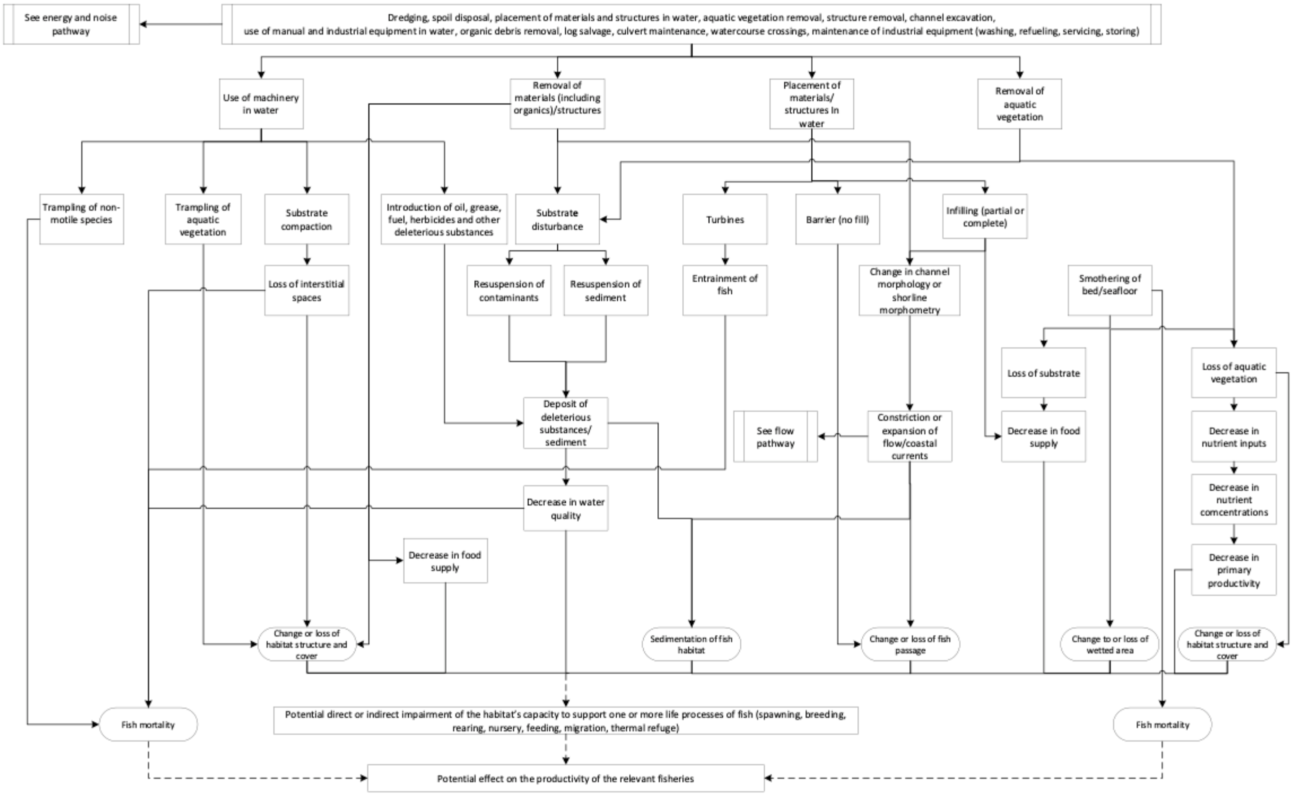


Figure 6: Draft (September 2020) Pathways of Effects diagram for in-water WUAs

1. Use of machinery in water

Use of machinery in water -> Trampling of non-motile species -> Fish mortality *(III*)*

Using heavy machinery such as hydraulic dredges in water has been documented to result in trampling of no-motile species, leading to mortality (Mercaldo-Allen and Goldberg 2011). Despite this logical connection, there are few empirical studies on the effects of using machinery in water (Courtice and Naser 2020). In general, species with lower mobility are more vulnerable to localized habitat impacts due to their inability to escape harmful conditions, such as rapid temperature changes (Szekeres et al. 2016). To avoid being trampled by equipment, fish and other organisms would need to have the ability to detect the threat and effectively avoid it, and have the movement response that involves sensory, cognitive, and locomotor capabilities (Nathan et al. 2008). Although there is no direct evidence of this regarding using machinery in water, less-mobile species are likely more vulnerable to this impact in general. This may include species that fail to avoid trampling for a variety of reasons. For example, species such as those in the Gobiidae (gobies) and Cottidae (sculpins) have behavioral tendencies to hide in interstitial spaces, which may increase their vulnerability to mortality from trampling. Although there is a general dearth of evidence on this issue, it would be logical to alter 'non-motile species' to 'less motile species and life stages' [1]. For the definition of motile, please see DFO (2021).

Use of machinery in water -> Trampling of aquatic vegetation -> Change or loss of habitat structure and cover *(II*)*

Operating heavy machinery in water logically has the potential to trample aquatic vegetation that is rooted in the substrate (Mercaldo-Allen and Goldberg 2011). Aquatic vegetation plays an essential role in providing habitat structure and cover for a wide variety of fish species and life stages (Rozas and Odum 1988; Bettoli et al. 1993; Smokorowski and Pratt 2007). The use of machinery in water overall has a high likelihood of disturbing sediments (Barton 1977; Tiemann 2004; Mercaldo-Allen and Goldberg 2011), which warrants a connection from 'Use of machinery in water' to 'Substrate disturbance' [2]. Similar to the noise pathway, the operation of machinery can cause behavioral avoidance of the area by fish (Mueller-Blenkle et al. 2010) and hence, a connection could be added here from 'Use of machinery in water' 'see Noise and Energy PoE diagram' [3]. This adds a more direct connection to this impact, and hence, the higher-level connection may be removed [4].

Use of machinery in water -> Substrate compaction -> Loss of interstitial spaces -> Fish mortality *(II)*

Using heavy machinery in water has been documented to compact the substrate, reducing interstitial spaces, and these changes have been linked with changes in both fish and invertebrate abundances and community structure (Barton 1977; Tiemann 2004; Mercaldo-Allen and Goldberg 2011). However, the exact mechanism is not clearly documented, as the use of machinery in water results in a variety of impacts simultaneously, including substrate disturbance, causing sedimentation of fish habitat that also impacts interstitial spaces. Logically, any organisms that remain within the interstitial spaces as substrates are compacted are likely to be killed. Again, there are few studies directly on this issue (Courtice and Naser 2020).

Use of machinery in water -> Substrate compaction -> Loss of interstitial spaces -> Change or loss of habitat structure and cover *(I*)*

Using heavy machinery in water logically has the capacity to compact the substrate, reducing interstitial spaces (Mercaldo-Allen and Goldberg 2011). Interstitial spaces are an important component of fish habitat, offering structural cover from predators and water flows, as well as food sources (Kovalenko et al. 2012; Barriga et al. 2013; Gregor and Anderson 2016). Therefore, a connection may be added from 'Loss of interstitial spaces' to 'Decrease in food supply' [5].

Use of machinery in water -> Introduction of oil, grease, fuel, herbicides, and other deleterious substances -> Deposit of deleterious substances/sediment -> Decrease in water quality *(I*)*

In Canada the protection of freshwater resources requires that proponents working in-water ensure that equipment and machinery are in good operating condition, free of leaks, excess oil and grease, and serviced/fueled at a distance beyond a watercourse or surface waters (e.g., 30 meters; British Columbia's *Water Act, 1996*). Despite these regulations, grease, oil, fuel and other deleterious substances may leak from machinery (Nowak et al. 2019). Generally, deleterious substances decrease water quality, in-turn resulting in impairment to productive capacity, sublethal impacts to fish, and fish mortality (Khan et al. 2007; Malk et al. 2014; Gorcharoenwat et al. 2015; Jurcak et al. 2015). However, herbicides are unlikely to be introduced through commonly used machinery in water, and therefore could be removed from the pressure node [6]. Water quality is also directly linked to food supply for fishes, therefore, a connection may be added from 'Decrease in water quality' to 'Decrease in food supply' [7]. The exact nature of how water quality is defined and how it impacts fishes can vary depending on the ecosystem and fish species (Meador and Goldstein 2003; Seilheimer et al. 2007; Budy et al. 2011).

Use of machinery in water -> Introduction of oil, grease, fuel, herbicides, and other deleterious substances -> Deposit of deleterious substances/sediment -> Sedimentation of fish habitat *(I)*

Many contaminants settle into sediments, and hence, could be considered an integral part of fish habitat sedimentation (Wang et al. 2004; Robertson et al. 2006; Taylor and Owens 2009).

Additional considerations

As discussed in **GENERAL CONSIDERATIONS** above, there are a wide variety of ways in which these pressure pathways may influence food availability. For example, both removal of aquatic vegetation and trampling of less-mobile species have functional connections to food supply. We do not suggest these changes here to maintain simplicity and diagram tractability, but they could be considered.

2. Removal of materials (including organics)/structures

Removal of materials (including organics)/structures -> Change or loss of habitat structure and cover *(I)*

There is a logical and well supported pressure pathway connecting the removal of materials or structures from water and a change or loss of habitat structure (Smokorowski and Pratt 2007). The structural changes associated with activities such as dredging have been directly linked to changes in fish habitat suitability (Harvey 1986; Harvey and Lisle 1998). Generally, structural complexity is an important component of ecosystem productivity and biological community complexity (Smokorowski and Pratt 2007; Kovalenko et al. 2012).

Removal of materials (including organics)/structures -> Substrate disturbance -> Resuspension of contaminants -> Deposit of deleterious substances/sediment -> Decrease in water quality *(I)*

Removing structures and other materials from waterways can cause considerable disturbance to the substrate, leading to resuspension and deposition of sediments and any contaminants contained within (Robertson et al. 2006; Taylor and Owens 2009; Chapman et al. 2014). For example, dam removals are commonly conducted to restore ecosystem connectivity, with many positive long-term benefits (Catalano et al. 2007); during the removal process sedimentation can be extensive (Magirl et al. 2015) and have acute negative effects on the downstream aquatic community (Doeg and Koehn 1994; Anderson et al. 1998). Contaminant resuspension may occur from removal of materials in the course of a variety of in-water activities (Bednarek 2001; Suedel et al. 2008; Wenger et al. 2017). For instance, depending on the specific nature of a dredging operation, contaminant resuspension rates can range from 0.1-5% (Bridges et al. 2008, references therein), and these sediments impact fish habitat quality (Wilber and Clarke 2001; Erftemeijer and Robin Lewis 2006; Cabaço et al. 2008).

Removal of materials (including organics)/structures -> Substrate disturbance -> Resuspension of contaminants -> Deposit of deleterious substances/sediment -> Sedimentation of fish habitat *(I)*

As discussed above, this is a well-supported pathway. Contaminants that have been deposited in sediments become disturbed and re-suspended and ultimately settle back onto the substrate in new locations, resulting in negative impacts of sedimentation of fish habitat (Robertson et al. 2006; Taylor and Owens 2009; Kemp et al. 2011; Chapman et al. 2014).

Removal of materials (including organics)/structures -> Substrate disturbance -> Resuspension of sediment-> Deposit of deleterious substances/sediment -> Decrease in water quality *(I)*

Declines in water quality are well documented when removing materials from water (Reid et al. 2002, 2003, 2004).

Removal of materials (including organics)/structures -> Substrate disturbance -> Resuspension of sediment-> Deposit of deleterious substances/sediment -> Sedimentation of fish habitat *(I)*

As discussed above, this is a well-supported pathway (Robertson et al. 2006; Taylor and Owens 2009; Kemp et al. 2011; Chapman et al. 2014).

Removal of materials (including organics)/structures -> Change in channel morphology or shoreline morphometry -> Constriction or expansion of flow/coastal currents -> Change or loss of fish passage *(II*)*

Removal of materials from lotic systems (streams and rivers) has been shown to cause a reduction in the overall wetted area, producing more narrow channel morphology and higher water flow levels (Smokorowski and Pratt 2007 and references therein). Therefore, a direct connection from ‘Constriction or expansion of flow/coastal currents’ to ‘Change or loss of wetted area’ [8]. These changes have been linked extensively with changes in fish community and production, although not explicitly with a loss of fish passage, more so the associated changes to habitat quantity and quality (Smokorowski and Pratt 2007 and references therein). Yet, removal of artificial barriers is often conducted explicitly to improve fish passage, and does so effectively in many cases (Kemp and O’Hanley 2010). Notably, alterations to flows apply to a range of aquatic ecosystems, including tidal flows in coastal regions. Further, alterations to structures and/or ecosystem morphology can also impact wave attenuation and reflection patterns, causing further structural and chemical, and biological changes to the system.

Removal of materials (including organics)/structures -> Change in channel morphology or shoreline morphometry -> Constriction or expansion of flow/coastal currents -> Sedimentation of fish habitat *(I)*

The changes in channel morphology associated with removal of in-water structures have been documented to result in erosion of sediments and hence sedimentation of fish habitats downstream (Reid and Anderson 1999; Randle et al. 2015). Additionally, these habitat changes associated with ‘Changes in channel morphometry or shoreline morphometry’ are also directly related to ‘Change or loss of habitat structure and cover’, which may warrant a direct connection [9].

Additional considerations

Removal of structures such as dams and weirs can also result in stranding of fish and freshwater mussels from the upstream side of the removed structure (Sethi et al. 2004; Cooper 2011; Heise et al. 2013; Tiemann et al. 2018). Therefore, stranding could be added as a node in this pressure pathway connecting to fish mortality [10]. Further, activities such as dredging have been documented to cause fish entrainment (Griffith and Andrews 1981), warranting a connection from removal of materials to entrainment [11]. Structure removal can also enable access for invasive species (Vitule et al. 2012; Mclaughlin et al. 2013; Raabe and Hightower 2014). For example, following the removal of the Oak Street Dam in Wisconsin, invasive canary grass (*Phalaris arundinaceae*) quickly overwhelmed native plants in the newly exposed sediments (Stanley and Doyle 2003). 'Removal of materials (including organics)/structures' may be connected to 'Aquatic invasive species pathway (TBD)' [12].

The disturbance, suspension, and deposition of sediments, other contaminants and their effects are covered in this diagram; however, some alterations may improve the description of their mechanistic relationships and logical flow. Specifically, the introduction or resuspension of contaminants generally leads to decreases in water quality, then deposition subsequently occurs into substrates. Therefore, this pathway could be altered to: 'Resuspension of contaminants' -> 'Decrease in water quality' -> 'Deposit of deleterious substances' -> 'Contamination of fish habitat (new pressure node)' -> 'Potential direct or indirect…' [13]. Similarly, connections could be rearranged as: 'Resuspension of sediment' -> 'Decrease in water quality' -> 'Deposit of deleterious substances' -> 'Contamination of fish habitat' (new pressure node) -> 'Potential direct or indirect…' [14]. A direct connection then may be added from 'Resuspension of sediment' -> 'Sedimentation of fish habitat' [15]. Lastly, 'Introduction of oil, grease, fuel, and other deleterious substances' -> 'Decrease in water quality' -> 'Deposit of deleterious substances' -> 'Contamination of fish habitat' (new pressure node) -> 'Potential direct or indirect.' [16].

3. Placement of materials/structures in water

Placement of materials/structures in water -> Turbines -> Entrainment of fish -> Fish mortality *(I*)*

There is an extensive body of literature supporting the fact that turbines associated with hydropower facilities cause fish entrainment, which often results in fish stress, injury, and mortality from contact with the turbines/structure, and extreme and rapid changes in pressure (reviewed by Barnthouse 2013; Rytwinski et al. 2017; Algera et al. 2020). The impacts may be sublethal, and hence this end point could be altered to 'Sublethal effects and/or mortality' to be more comprehensive [17]. Considerable research, synthesis, and review has gone into characterizing the causes and mitigation strategies for fish entrainment in relation to hydropower facilities, including but not limited to dam flow management, turbine design modifications, diversion and deterrence devices, bypass structures and attractive devices. The rates of mortality from hydropower facilities depend on a complexity of factors related to ecosystem and facility characteristics, fish characteristics, and mitigation strategies.

Placement of materials/structures in water -> Barrier (no fill) -> Change or loss of fish passage *(I)*

A wide variety of structures are commonly placed in water that form barriers to fish passage, which may include dams, culverts, dikes, levees, floodgates and weirs, amongst others (Warren and Pardew 1998; O'Hanley and Tomberlin 2005; Kemp and O'Hanley 2010). The construction of these in-water structures often involves using fill (e.g., rock, sand and/or soil), but not exclusively. Notably, structures may form partial or complete barriers to upstream fish passage even if the watercourse is not fully obstructed, such is often the case with culverts (Kahler and Quinn 1998; Peake 2008; Briggs and Galarowicz 2013). Even structures specifically designed to enable fish passage around human-made barriers may not be effective, and remain at least partial obstructions to fish passage (Bunt et al. 2012). The extent to which a structure forms a fish passage barrier depends on interactions with water flow, geomorphology, fish behavioral responses and physiological characteristics (Bunt et al. 2012; Jones and Hale 2020).

Placement of materials/structures in water -> Infilling (partial or complete) -> Change in channel morphology or shoreline morphology -> Constriction or expansion of flow/coastal currents -> Change or loss of fish passage *(I)*

As discussed above, this is a well-supported pathway. In relation to infilling specifically, the degree to which the watercourse is blocked and hydrological/water flow patterns are altered likely influence fish passage success (Bunt et al. 2012).

Placement of materials/structures in water -> Infilling (partial or complete) -> Decrease in food supply *(I)*

Infilling associated with activities such as road construction or shoreline armouring often involve placing materials such as crushed rock in the water, replacing natural substrates, resulting in lower productivity and fish food availability (Tsui and McCart 1981; Armitage and Gunn 1996; Munsch et al. 2017; Dugan et al. 2018; Macura et al. 2019; Chhor et al. 2020). These impacts have been characterized extensively through numerous studies and a systematic review (Macura et al. 2019), and include physical alterations to the habitat as well as alterations to hydrodynamic energy and water flow, causing knock-on effects to habitat conditions.

Placement of materials/structures in water -> Infilling (partial or complete) -> Change in channel morphology or shoreline morphology -> Constriction or expansion of flow/coastal currents -> Sedimentation of fish habitat *(I*)*

Infilling often causes direct changes to watercourse channel stability and morphology (Reid and Anderson 1999), resulting in sedimentation of fish habitat (Reid et al. 2002, 2003, 2004). Further, this process may also directly affect water quality depending on the material used (e.g., concrete), where a connection may be added [18].

Additional considerations

Placement of a wide variety of materials may result in the sedimentation of fish habitat through mechanisms beyond alterations in flow patterns (Chessman et al. 1987; Anderson et al. 1998), hence, a high-level connection from ‘Placement of materials’ to ‘Sedimentation of fish habitat’ may be warranted [19]. Similarly, fish stranding may also occur due to the changes in wetted area, channel morphology and flow, or below hydropeaking dams (Clarke et al. 2008). This process is covered in the flow pathway, hence a connection may be added from ‘Placement of materials/structures in water’ to 'See Flow pathway' [20].

4. Removal of aquatic vegetation

Removal of aquatic vegetation -> Substrate disturbance *(II)*

The extension of the pathways beyond substrate disturbance have been covered above in relation to Removal of materials and Placement of materials pressure pathways, and therefore will not be further discussed here. Aquatic macrophytes (vegetation) primarily, but not exclusively, root themselves into substrates, especially fine substrates such as mud, clay, and sand from which essential nutrients can be extracted (Barko et al. 1986). Vegetation plays an essential role in sediment stability (Wang et al. 2015), and hence, logically, removal of vegetation including their root structures would disturb sediments or make them susceptible to resuspension after the removal. However, there is little scientific literature specifically addressing this. Indeed, although riparian vegetation removal was discussed extensively, aquatic vegetation removal was not included in recent reviews of causes and consequences of sedimentation on fish and fish habitat (Robertson et al. 2006; Chapman et al. 2014). Yet, the potential to disturb sediments is recognized through regulation – legal approaches to remove aquatic vegetation generally do not disturb plant roots and sediments (Hicks and Sager 2009). For example, in Ontario, landowners may remove aquatic vegetation from portions of their shoreline using mechanical or chemical methods that generally target the above-ground vegetative structure of the plant (Hicks and Sager 2009). Hence, vegetation removal can result in substrate disturbance, but there are many approaches available that avoid disturbing substrates.

Removal of aquatic vegetation -> Loss of aquatic vegetation -> Decrease in nutrient input -> Decrease in nutrient concentrations -> Decrease in primary productivity *(I*)*

Aquatic vegetation forms an important component of primary productivity and forms structural fish habitat for a range of purposes that may include foraging, refuge, or spawning (Rozas and Odum 1988; Smokorowski and Pratt 2007 and references therein). Removal or loss of aquatic vegetation has therefore been documented to have direct effects on fish communities and productivity (Bettoli et al. 1993; Midwood and Chow-Fraser 2012). Aquatic vegetation also shapes other aspects of aquatic habitat through stabilizing sediments, altering water flow patterns, and water chemistry (Wang et al. 2015). Extensive review and discussion on this topic is included in (Smokorowski and Pratt 2007). Therefore, a connection may be added from ‘Removal of aquatic vegetation’ to ‘Change or loss of habitat structure and cover’ [21]. This pathway is accurate and complete; however, there is detail included in these nodes beyond what is included in other components of these diagrams, and many of the intermediate nodes may be removed, connecting ‘Removal of aquatic vegetation’ directly to ‘Decrease in primary productivity’ [22,22]. As discussed above, aquatic vegetation plays a very important role in food supply for many fishes, so a connection may be added from ‘Removal of aquatic vegetation’ to ‘Decrease in food supply’ [23]. Removal of aquatic vegetation creates greater opportunity for species invasions (Valley et al. 2004; Hicks and Sager 2009), therefore a connection may be added from ‘Removal of aquatic vegetation’ to ‘see Aquatic Invasive Species pathway (TBD)' [24].

5. Smothering of bed/seafloor

Initial considerations

Currently ‘Smothering of bed/seafloor’ is included at the start of an independent pressure pathway, yet, it occurs predominantly due to placement of materials/structures in water, and hence, could be included as a component of this pressure pathway, where further, ‘Placement of materials/structures in water’ is placed above, and connected to, ‘Smothering of bed/seafloor’ [25]. This would form an important connection between sedimentation of fish habitat and fish mortality, which is currently lacking.

Smothering of bed/seafloor -> Fish mortality *(I)*

Smothering of bed/seafloor can result in fish mortality, which is especially well documented in the case of sedimentation of fish habitat, which can smother fish eggs or larvae and result in mortality (reviewed in Kemp et al. 2011; Chapman et al. 2014). However, smothering is considered to be implicit to the sedimentation process. Here, we considered smothering under the definition of the placement of physical materials into aquatic habitats, covering the bed/seafloor. Placement of other materials, such as cement or rock walls in shoreline armoring or construction of dams involves the placement of materials on top of natural substrates, which would naturally smother any organisms contained within (Munsch et al. 2017). This could include less-motile invertebrates and fishes, as discussed in relation to use of machinery in water above.

Smothering of bed/seafloor -> Change or loss of wetted area *(I)*

As discussed above, smothering of the bed/seafloor is caused by placement of materials in water, and is directly related to change or loss of wetted area.

Smothering of bed/seafloor -> Loss of substrate -> Change or loss of food supply *(I)*

Infilling associated with activities such as road construction or shoreline armouring often involve placing materials such as crushed rock in the water, replacing natural substrates, resulting in lower productivity and fish food availability (Tsui and McCart 1981; Armitage and Gunn 1996; Macura et al. 2019; Chhor et al. 2020). These impacts have been characterized through a systematic review (Macura et al. 2019).

Overview of potential alterations of the in-water PoE diagram

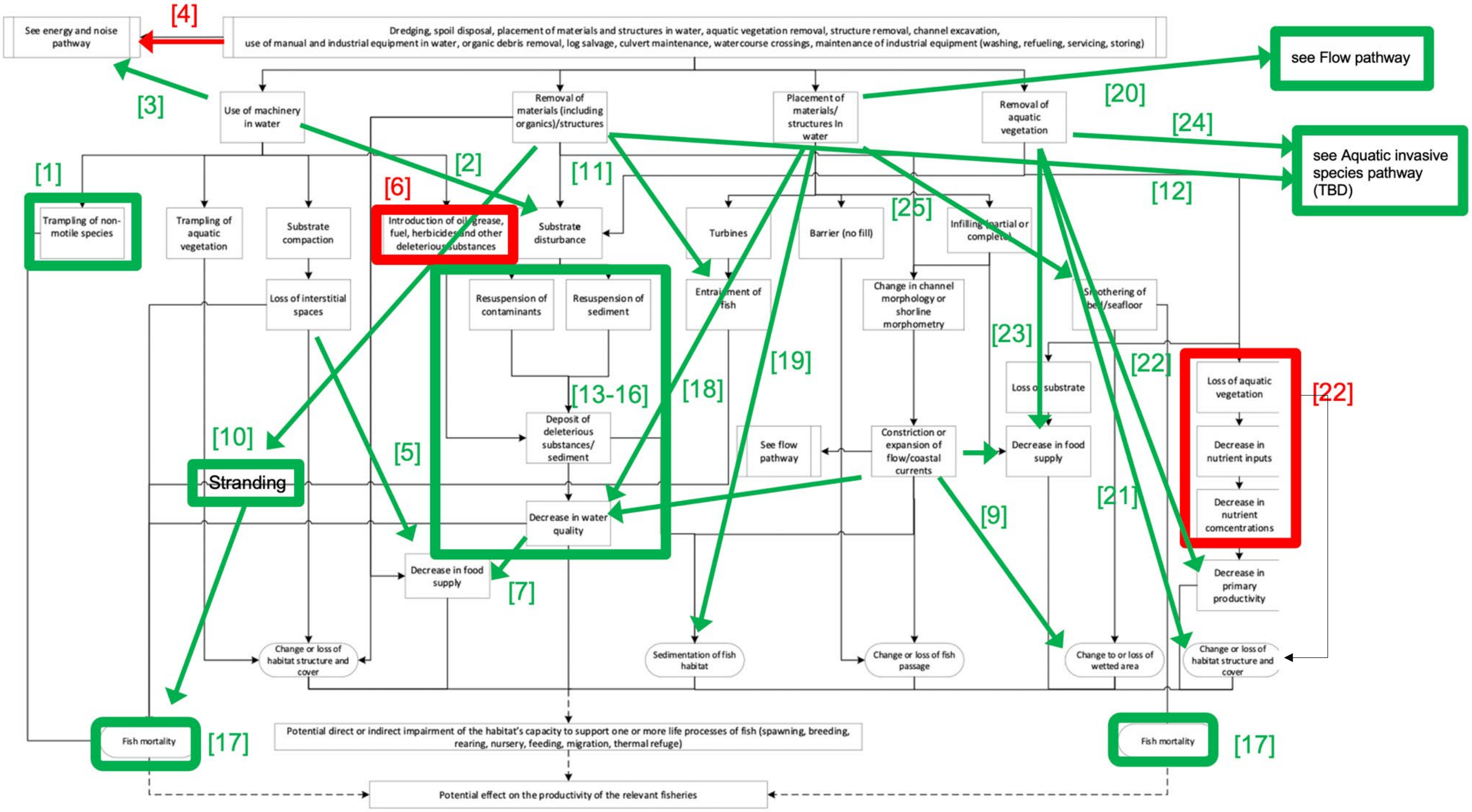


Figure 7: Overview of potential alterations to the draft (September 2020) Pathways of Effects diagram for in-water WUAs. Additional lines indicate connections that may be added (green) or removed (red); additional boxes indicate alterations or additions to pressures or endpoints.

FLOWS DIAGRAM

The proposed PoE diagram for WUAs affecting flows (***Figure 8***) includes: water management, hydro dams, cofferdams, pump arounds, diversion channels, flumes, weirs, constriction/expansion of flow/coastal currents, water extraction, and wastewater management.

These WUAs are proposed to apply the following pressures or sub-activities:

1. **Water diversion**
2. **Dewatering/pumping**
3. **Water level/flow modification (change in hydraulics) including impoundments**
4. **Introduction of wastewater**

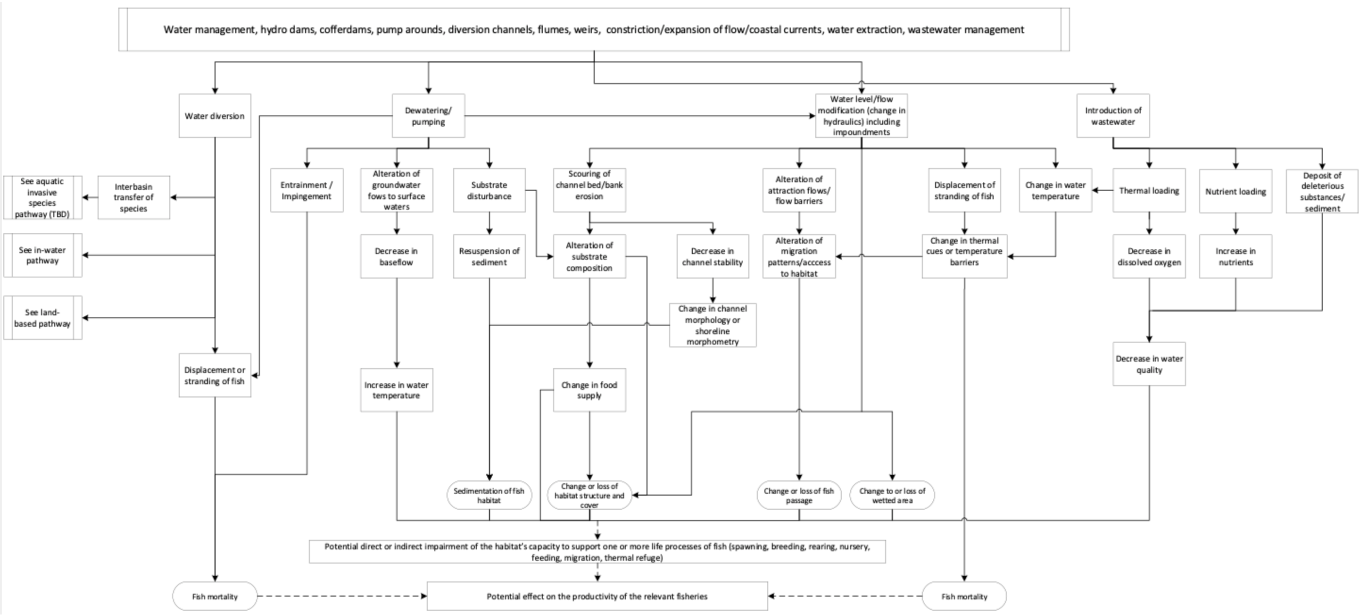


Figure 8: Draft (September 2020) Pathways of Effects diagram for WUAs affecting flows.

1. Water diversion

Water diversion -> Inter-basin transfer of species *(I*)*

The diversion of water can form connections between previously disparate aquatic ecosystems, which has been documented to enable species invasions (Zhan et al. 2015; Qin et al. 2019). Further, the diversion of water often results in altered conditions within the affected systems, which creates opportunities for introduced or invasive species to become established in new ecosystems (Stromberg et al. 2007). This is a well-supported pathway, although it involves more than just species transfer, and could potentially be altered to 'Increased species inter-basin transfer/risk of invasives' [1] to be more comprehensive. Here, we considered inter-basin transfer as the movement of fishes or other organisms (e.g., invertebrates, plants, pathogens) between aquatic ecosystems that are not naturally connected. This may include movement of species that are native within a region, but they are not native to a given ecosystem.

Water diversion -> Displacement or standing of fish -> Fish mortality *(I*)*

Water diversion has been documented in numerous cases to result in fish displacement, fish stranding, and fish mortality (Steele and Smokorowski 2000; Halleraker et al. 2003; Moyle and Israel 2005; Clarke et al. 2008; Nagrodski et al. 2012; Irvine et al. 2015). The extent to which fish become displaced or entrained by water diversion can be minimized using screen barriers or deterrent or attraction devices, although their efficacy is varied (Moyle and Israel 2005; Lemasson et al. 2008; Nagrodski et al. 2012; Barnthouse 2013). As in many cases throughout all PoE diagrams reviewed here, fish may also experience sub-lethal effects in addition to mortality, and hence, this endpoint could be altered to ‘Sublethal effects and/or mortality’ [2].

Additional considerations

The process of extracting water or moving it between waterbodies or sections of the same waterbody through water diversion has been documented to have impacts on water temperature, especially in smaller, cold water streams (Meier et al. 2003). Therefore, a connection may be added from ‘Water diversion' to ‘Altered water temperature’ [3]. Further, as discussed and referenced above, water diversion has direct impacts on water levels and flow characteristics, hence a direct connection from ‘Water diversion’ to ‘Water level/flow modification (change in hydraulics) including impoundments’ may be added [4]. By forming this connection, the connection from ‘Water diversion’ to ‘Displacement or stranding of fish’ to ‘Fish mortality’ becomes redundant and is no longer required [5].

2. Dewatering/pumping

Dewatering/pumping -> Displacement or stranding of fish *(I)*

We interpreted dewatering/pumping as any activity that actively extracts water from an aquatic ecosystem. Any activity that withdraws water causing major declines in water levels can result in fish stranding or displacement (reviewed by Steele and Smokorowski 2000; Halleraker et al. 2003; Clarke et al. 2008; Nagrodski et al. 2012; Irvine et al. 2015). Dewatering/pumping has been linked directly with fish displacement and stranding (Fischer and Kummer 2000; Falke et al. 2011).

Dewatering/pumping -> Entrainment/impingement -> Fish mortality *(I)*

Dewatering due to hydropeaking at hydroelectric dams is well-documented to cause fish entrainment/impingement and mortality (Barnthouse 2013; Rytwinski et al. 2017; Algera et al. 2020). This issue has also been documented with dewatering/pumping for industrial, agricultural, and municipal water supply, as well as during in-water works during construction requiring site isolation/dewatering (Moyle and Israel 2005; Kemp 2015).

Dewatering/pumping -> Alteration of groundwater flows to surface waters -> Decrease in baseflows -> Increase in water temperature *(I*)*

It is well documented that the extraction of groundwater can result in reduced groundwater flows to surface waters, and decreases in baseflows (Blackport et al. 1995; Power et al. 1999; Fleckenstein et al. 2004; Chu et al. 2008; Perkin et al. 2017). As discussed in the land-based PoE, this can result in increases in temperature in the summer months, or decreases in temperature in the winter months, both of which can have negative effects on fish. Therefore, this pressure could be changed to ‘Altered water temperature’ [6]. Decreases in baseflow also result in changes [decreases] in food supply (Weisberg and Burton 1993), which is an additional connection that may be added [7]. Changes in water temperature may also result in direct fish mortality or sublethal effects if temperatures increase or decrease outside of species tolerances (Brett 1956), warranting a connection [8].

Dewatering/pumping -> Substrate disturbance -> Resuspension of sediment -> Sedimentation of fish habitat *(I*)*

Dewatering takes a variety of forms which likely cause varied levels of substrate disturbance. Flashy flows (rapid and varied high intensity flows), often associated with hydropeaking or dam water management, cause high rates of sediment erosion and transport, resulting in sedimentation of fish habitat (Robertson et al. 2006; Batalla and Vericat 2009; Chapman et al. 2014). This is a supported pathway, although the extent to which various dewatering activities, such as water extraction, result in substrate disturbance is not well documented. Sedimentation of fish habitat may also result directly in fish mortality, especially in the egg stage (Robertson et al. 2006). Therefore, a connection may be added from 'Sedimentation of fish habitat' to 'Sublethal effects and/or mortality' [9].

Dewatering/pumping -> Substrate disturbance -> Alteration of substrate composition -> Change in food supply -> Change or loss of habitat structure and cover *(I*)*

The relationship between dewatering/pumping and substrate disturbance is discussed above. Sedimentation of fish habitat directly results in altered substrate composition, filling interstitial spaces that offer structural habitat and food supply to fish (Robertson et al. 2006; Chapman et al. 2014). Further, major dewatering can affect soil nutrient profiles impacting primary productivity (James et al. 2004). The connections from 'Alteration of substrate composition' and 'Change in food supply' is well supported, as is that from 'Alteration of substrate composition' and 'Change or loss of habitat structure and cover'. However, there is no causal relationship between 'Change in food supply' and 'Change or loss of habitat structure and cover'; this connection could be removed or reversed in the direction of connectivity [10].

3. Water level/flow modification (change in hydraulics) including impoundments

Water level/flow modification -> Scouring of channel bed/bank erosion -> Alteration of substrate composition -> Change in food supply -> Change or loss of habitat structure or cover *(I*)*

There is a well-supported cause and effect relationship between alteration of water levels and water flows with channel bed scouring and bank erosion (Clarke et al. 2008; Batalla and Vericat 2009; Shen and Diplas 2010). Generally, fine sediments tend to be eroded from high flow areas and redistributed to low-flow locations, hence altering substrate composition. This has been linked directly to changes in fish communities (Cushman 1985; Power et al. 1996). As discussed above, sedimentation of fish habitat often causes changes in food supply as well as change or loss of habitat structure and cover (Robertson et al. 2006; Chapman et al. 2014), although there is no cause-and-effect relationship, unless the direction of the connection were reversed [10]. Further, to be more inclusive of all common terminology used across diverse aquatic ecosystems in Canada, 'shoreline' may be added to the pressure node, 'Scouring of channel bed/bank erosion' node, altering it to 'Scouring of the channel bed and bank/shoreline erosion' [11].

Water level/flow modification -> Scouring of channel bed/bank erosion -> Decrease in channel stability -> Change in channel morphology or shoreline morphology -> Sedimentation of fish habitat *(I*)*

As discussed above, there is a well-established connection between water level/flow modification and scouring of channel bed and bank/shoreline erosion resulting in sedimentation of fish habitat. This connection is direct and occurs independently of channel stability and morphology; therefore, a direct connection could be made from 'Scouring of the channel bed and bank/shoreline erosion' to 'Sedimentation of fish habitat' [12]. Longer-term, the impacts that water level/flow modification has on channel stability and channel and shoreline morphology may also result in continued erosion and sedimentation of fish habitat (Clarke et al. 2008). Notably, alterations in water flow alter sediment supply rates more generally (e.g., reduced flow would reduce sediment supply). Therefore, an 'Altered sediment supply' node may be added, creating the pathway: 'Water level/flow modification' -> 'Altered sediment supply' -> 'Change in channel morphology or shoreline morphometry' [13]. Here, we considered morphometry as the physical shape and structure of shoreline/channel/lake bed. Further, these changes related directly to habitat structure and cover, therefore, a connection may be added from 'Change in channel morphology or shoreline morphometry' to 'Change or loss of habitat structure or cover' [14].

Water level/flow modification -> Alteration of attraction flows/flow barriers -> Alteration of migration patterns/access to habitat -> Change or loss of fish passage *(I*)*

Water flow plays an essential role in fish passage through both attraction of fishes to passable locations as well as limiting passage through flow barriers. This is most studied in relation to dams and related fish passage structures (reviewed by Coutant and Whitney 2000; Bunt et al. 2012). In addition to changes in fish passage, alterations of water flow can also impact other processes such as spawning behavior and success (Auer 1996). For a variety of reasons, alterations in flow patterns can have substantive effects on fish community composition, likely through a range of sublethal effects (Cushman 1985; Bain et al. 1988). There is a DFO framework developed for management of flow modifications that may serve as a reference for assessing impacts (DFO 2013), a toolkit developed for fish passage, ecological flow management and fish habitat works (Katopodis 2005), and a meta-analysis on the effects of water management on aquatic communities (Haxton and Findlay 2008). Overall, there are a variety of ways in which flows may affect access to habitat and migration success beyond just attraction flows. Therefore, to be more encompassing, 'Alteration of attraction flows/flow barriers' may be removed, connecting 'Water level/flow modification (change in hydraulics) including impoundments' to 'Alteration of migration patterns/access to habitat' directly [15,15]. Further, although reduced migration success or habitat access is often related to reduced fish passage, this can also occur independent of passage issues, hence a direct connection could be made from 'Alteration of migration patterns/access to habitat' to 'Sublethal effects and/or mortality' [16].

Water level/flow modification -> Change to or loss of wetted area *(I)*

There is a direct connection between modification of water levels/flows to change or loss of wetted area as water levels and wetted area are functionally synonymous.

Water level/flow modification -> Change or loss of habitat structure and cover *(I)*

In addition to impacting wetted area, in some cases the modification of water level and/or flow can also influence structural habitat availability. This is documented most often in respect to key shallow water habitat that often supports spawning, early life stages, as well as structure for general refuge and foraging (Zorn et al. 1998; Freeman et al. 2001; Grabowski and Isely 2007; Gaeta et al. 2014).

Water level/flow modification -> Displacement or* stranding of fish -> Change in thermal cues or temperature barriers -> Fish mortality *(I*)*

The * above indicates a spelling error in the current PoE diagram. As discussed prior, there is a well-established relationship between modification of water level and/or flow and fish stranding and displacement (reviewed by Steele and Smokorowski 2000; Halleraker et al. 2003; Clarke et al. 2008; Nagrodski et al. 2012; Irvine et al. 2015). Alterations in the timing and intensity of water flow from natural regimes can substantially alter fish displacement rates (Harvey 1987; Liebig et al. 1999). Studies consistently find seasonal and diel variation in stranding probability, which may be related in some cases to water temperature. For example, cold water temperatures may limit fish swimming capabilities, and in turn their capacity to move effectively to safe water during rapid water level declines. However, the above syntheses revealed little evidence of the role of thermal cues and temperature barriers in fish stranding. There are a variety of reasons why fish become displaced or stranded, the primary driver being rapid changes in water flow. Therefore, ‘Change in thermal cues or temperature barriers’ may be removed, making a direct connection from 'Displacement or stranding of fish' to 'Sublethal effects and/or fish mortality' [17,17].

Water level/flow modification -> Displacement or* stranding of fish -> Change in thermal cues or temperature barriers -> Alteration of migration patterns/access to habitat -> Change or loss of fish passage *(I*)*

It is well documented that reductions in water flow often cause increases in riverine water temperature, which has been implicated in changes in fish productivity and community structure (Bunn and Arthington 2002; Clarke et al. 2008; Bae et al. 2016). Riverine fishes also commonly rely on temperature and/or flow cues for seasonal movements or migration, which has been documented in relation to spawning (e.g., Rusak and Mosindy 1997; Tornabene et al. 2020). Yet, this specific pathway involving fish displacement or stranding, followed by temperature-related impacts on habitat access and subsequent loss of fish passage, is not well supported in the literature. As discussed above, alterations to this pathway would improve accuracy and comprehensiveness [17,17].

Water level/flow modification -> Change in water temperature -> Change in thermal cues or temperature barriers -> Fish mortality *(II)*

As discussed above, changes in water flow and associated changes in water temperature in riverine habitats have well documented connections to changes in fish productivity and community structure (Bunn and Arthington 2002; Clarke et al. 2008; Bae et al. 2016), as well as changes in thermal cues or temperature barriers (e.g., Rusak and Mosindy 1997; Tornabene et al. 2020). There is certainly evidence linking water level or flow modifications and associated water temperature changes directly to fish mortality through stranding, as discussed above. Declines in water flow and increases in water temperature are well documented to have lethal and sublethal effects on salmonids during their riverine spawning migration (Farrell et al. 2008). This could be considered a form of temperature barrier that limits access to spawning habitat. This would be more accurately defined as an exclusion than a barrier, although we do not suggest this change explicitly here, it could be considered. As discussed above, sublethal effects and fish mortality can be caused by changes in temperature independent of thermal cues or temperature barriers, therefore, a direct connection could be added from ‘Altered water temperature’ -> ‘Sublethal effects and/or mortality’ [18].

Water level/flow modification -> Change in water temperature -> Change in thermal cues or temperature barriers -> Alteration of migration patterns/access to habitat -> Change or loss of fish passage *(I)*

As discussed above, this is a well-supported pathway (Rusak and Mosindy 1997; Bunn and Arthington 2002; Clarke et al. 2008; Bae et al. 2016; Tornabene et al. 2020).

4. Introduction of wastewater

Introduction of wastewater -> Thermal loading -> Change in water temperature -> Change in thermal cues or temperature barriers -> Fish mortality *(I)*

Wastewater is a broad term that may refer to any water that has been contaminated by human use, and hence comes from a wide variety of sources – it may have a variety of potentially harmful characteristics, depending on the source. Wastewater effluents from sources such as urban water treatment or nuclear power plants are often warmer than ambient aquatic ecosystem temperatures, especially during colder environmental conditions (Kinouchi et al. 2007; McCallum et al. 2019). These warm effluents have been associated with substantially altered fish communities in affected areas (McCallum et al. 2019), and may in some cases attract fish but have negative impacts on their fitness, serving as an ecological trap (Mehdi et al. 2021). Rapid changes in effluent flow rates from nuclear power facilities and associated changes in temperature have been documented to cause fish mortality and sublethal effects (Coutant 1977). The effects of wastewater on fish may be highly variable depending on species characteristics, including their behavioral responses (attraction or repulsion), and physiological tolerances of varied and often adverse conditions at effluents (Burns et al. 2019; McCallum et al. 2019; Mehdi et al. 2021).

Introduction of wastewater -> Thermal loading -> Change in water temperature -> Change in thermal cues or temperature barriers -> Alteration of migration patterns/access to habitat -> Change or loss of fish passage *(III)*

The connections from introduction of wastewater to thermal cues and temperature barriers are discussed above and well-supported. Water temperature often has a major impact on fish passage success as well (reviewed by Coutant and Whitney 2000; Bunt et al. 2012). However, this pressure pathway from wastewater to fish passage has not been well documented. It is plausible given the functional connections amongst each component, although the prevalence of this issue is unknown. However, to be concise, ‘Thermal loading’ could be removed, retaining the key connection from ‘Introduction of wastewater’ -> ‘Change in water temperature’ [19,19].

Introduction of wastewater -> Thermal loading -> Decrease in dissolved oxygen -> Decrease in water quality (*I)**

Introduction of wastewater has been well documented to increase both water temperature and dissolved oxygen; however, dissolved oxygen is not specifically referenced throughout these diagrams, rather it is considered to be an integral part of water quality (DFO 2021). Therefore, ‘Decrease in dissolved oxygen’ may be removed, connecting ‘Thermal loading’ directly to ‘Decrease in water quality’ [20,20].

Introduction of wastewater -> Nutrient loading -> Increase in nutrients -> Decrease in water quality *(I*)*

Wastewater may contain high concentrations of nutrients such as phosphorus and nitrogen, especially that from certain agricultural, industrial, and urban sources. This has a well-documented impact on water quality (Carey and Migliaccio 2009), and has been linked directly with changes in fish communities (Tetreault et al. 2013). However, to be concise, ‘Nutrient loading’ could be removed, retaining the key connection from ‘Introduction of wastewater’ -> ‘Increase in nutrients’ [21,21].

Introduction of wastewater -> Deposit of deleterious substances -> Decrease in water quality *(I*)*

In addition to nutrients, wastewater also commonly contains a wide variety of substances that can be harmful to fish health (Schlacher et al. 2007; Vajda, Alan et al. 2008; Lozano et al. 2012). These chemicals can have a diversity of impacts, including reduced reproductive success (Vajda, Alan et al. 2008). There is a strong basis of support for connecting 'Decrease in water quality' to 'Sublethal effects and/or mortality' [22].

Additional considerations

Introduction of wastewater influences not only water quality, but also water quantity, as it becomes a water source for effluent systems (Carey and Migliaccio 2009; Tetreault et al. 2013). Therefore, a connection could be added from ‘Introduction of wastewater’ to ‘Water level/flow modification (change in hydraulics) including impoundments’ [23]. In particular, variability in wastewater outflows may affect systems that become highly dependent upon those flows for maintenance of wetted area. Additionally, the effects being described within this diagram are broadly related to both water flow and water levels; therefore, the name of this diagram could be altered for ‘WUAs affecting flows’ to ‘WUAs affecting water levels and flows’ [24]. Last, ‘pumping’ is included in the ‘dewatering/pumping’ pressure node, but pumping is a WUA. Hence, ‘pumping’ may be moved to the broader description of WUAs, altering the pressure node to ‘dewatering’ [25].

Overview of potential alterations to the flows PoE diagram

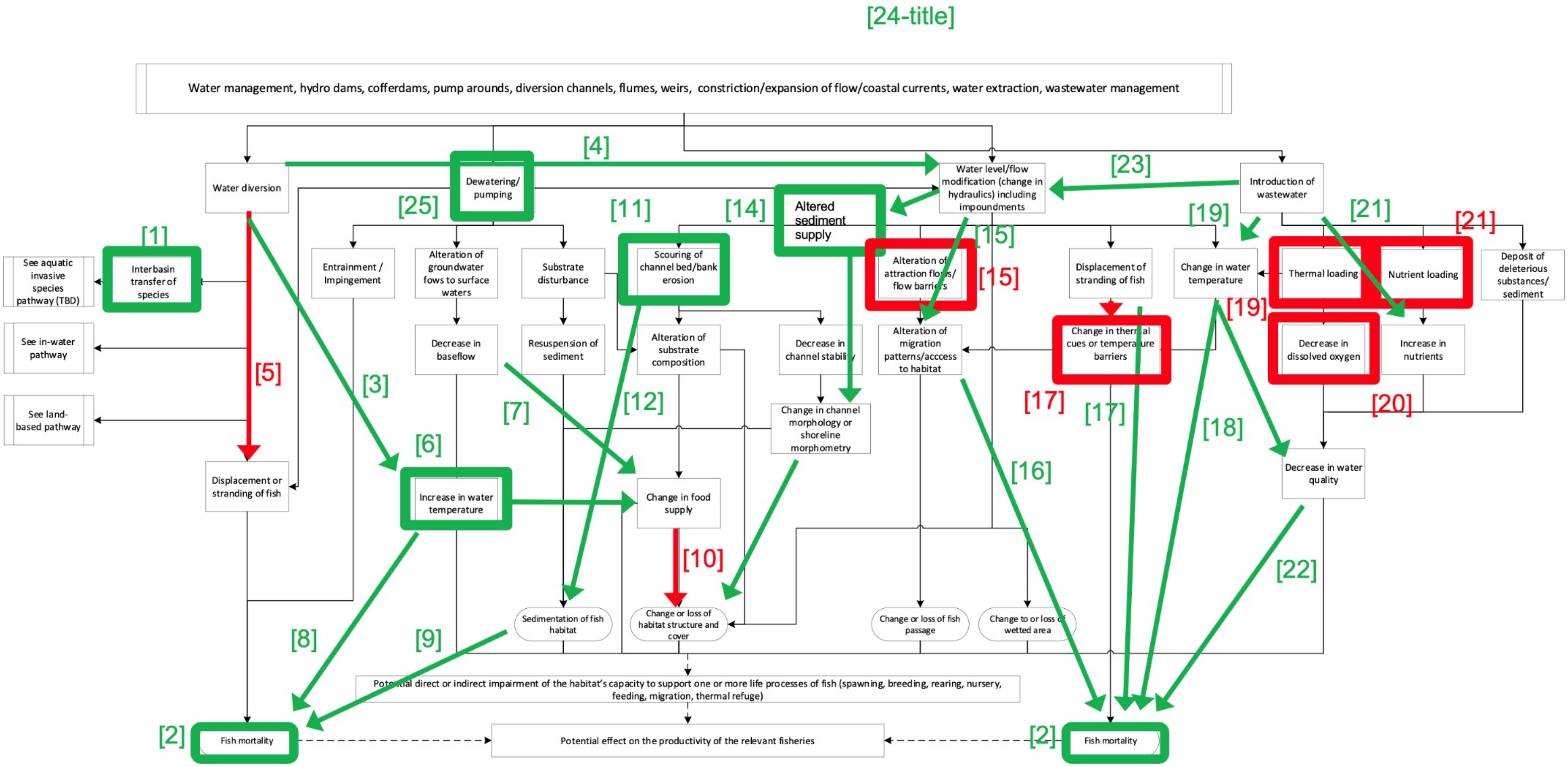


Figure 9: Overview of potential alterations to the draft (September 2020) Pathways of Effects diagram for WUAs affecting flows. Additional lines indicate connections that may be added (green) or removed (red); additional boxes indicate alterations or additions to pressures or endpoints.

CONCLUSIONS

The recently amalgamated four PoE diagrams aim to provide a comprehensive and accurate representation of the majority of common WUAs and their potential impacts on fish and fish habitat for the purposes of FFHPP communication and decision making. Here we propose a range of potential changes and additions to these diagrams to help meet these ends. It is important to recognize the balance between representing the high level of complexity of the interrelationships of WUAs, pressures, and endpoints, and maintaining tractable models for their expressed purpose of FFHPP communication and decision making. Recognizing this balance, this review and proposed changes to draft PoE diagrams are not completely comprehensive of every way in which WUAs, pressures, and endpoints are potentially interconnected, but focus on core connectivity and diagram functionality. Consideration of this trade-off while integrating these recommendations is important to ensure maximum validity and applicability by FFHPP, and further development and application will require interpretation of these implicit complexities within simplified diagrams. It may be of value to assess how readily key links in these diagrams can be broken, which may be informed in part by the resources provided in this document and the associated literature database. To employ ecosystem-based management accounting for the cumulative effects of activities on ecosystem state, there is a need to further identify interconnectivity amongst these PoE diagrams, as well as the how various pressure pathways interact to produce cumulative impacts.

REFERENCES CITED

Abbe, T.B., and Montgomery, D.R. 1996. Large woody debris jams, channel hydraulics and habitat formation in large rivers. Regul. Rivers Res. Manag. doi:10.1002/(sici)1099-1646(199603)12:2/3<201::aid-rrr390>3.0.co;2-a.

Abernethy, B., and Rutherfurd, I.D. 1998. Where along a river’s length will vegetation most effectively stabilise stream banks? Geomorphology. doi:10.1016/S0169-555X(97)00089-5.

Adams, S.M., Ham, K.D., Greeley, M.S., LeHew, R.F., Hinton, D.E., and Saylor, C.F. 1996. Downstream gradients in bioindicator responses: Point source contaminant effects on fish health. Can. J. Fish. Aquat. Sci. doi:10.1139/f96-191.

Algera, D.A., Rytwinski, T., Taylor, J.J., Bennett, J.R., Smokorowski, K.E., Harrison, P.M., Clarke, K.D., Enders, E.C., Power, M., Bevelhimer, M.S., and Cooke, S.J. 2020. What are the relative risks of mortality and injury for fish during downstream passage at hydroelectric dams in temperate regions? A systematic review. doi:10.1186/s13750-020-0184-0.

Anderson, P.G., Fraikin, C.G.J., and Chandler, T.J. 1998. Impacts and recovery in a coldwater stream following a natural gas pipeline crossing installation. *In* Proceedings of the International Pipeline Conference, IPC. doi:10.1115/ipc1998-2120.

Angermeier, P.L., and Karr, J.R. 1984. Relationships between Woody Debris and Fish Habitat in a Small Warmwater Stream. Trans. Am. Fish. Soc. doi:10.1577/1548-8659(1984)113<716:rbwdaf>2.0.co;2.

Araújo, C.V.M., Silva, D.C.V.R., Gomes, L.E.T., Acayaba, R.D., Montagner, C.C., Moreira-Santos, M., Ribeiro, R., and Pompêo, M.L.M. 2018. Habitat fragmentation caused by contaminants: Atrazine as a chemical barrier isolating fish populations. Chemosphere. doi:10.1016/j.chemosphere.2017.11.014.

Armitage, P.D., and Gunn, R.J.M. 1996. Differential response of benthos to natural and anthropogenic disturbance in 3 lowland streams. Int. Rev. der Gesamten Hydrobiol. **81**: 161–181.

Armon, R.H., and Starosvetsky, J. 2015. Point source pollution indicators. *In* Environmental Indicators. doi:10.1007/978-94-017-9499-2_29.

Auer, N.A. 1996. Response of Spawning Lake Sturgeons to Change in Hydroelectric Facility Operation. Trans. Am. Fish. Soc. doi:10.1577/1548-8659(1996)125<0066:roslst>2.3.co;2.

Bach, L., Nielsen, M.H., and Bollwerk, S.M. 2017. Environmental Impact of Submarine Rock Blasting and Dredging Operations in an Arctic Harbor Area: Dispersal and Bioavailability of Sediment-Associated Heavy Metals. Water. Air. Soil Pollut. doi:10.1007/s11270-017-3363-z.

Bae, M.J., Merciai, R., Benejam, L., Sabater, S., and García-Berthou, E. 2016. Small Weirs, Big Effects: Disruption of Water Temperature Regimes with Hydrological Alteration in a Mediterranean Stream. River Res. Appl. doi:10.1002/rra.2871.

Bain, M.B., Finn, J.T., and Booke, H.E. 1988. Streamflow regulation and fish community structure. Ecology. doi:10.2307/1940436.

Baker, D.B., Richards, R.P., Loftus, T.T., and Kramer, J.W. 2004. A new flashiness index: Characteristics and applications to Midwestern rivers and streams. J. Am. Water Resour. Assoc. doi:10.1111/j.1752-1688.2004.tb01046.x.

Banks, D., Younger, P.L., Arnesen, R.T., Iversen, E.R., and Banks, S.B. 1997. Mine-water chemistry: The good, the bad and the ugly. Environ. Geol. doi:10.1007/s002540050204.

Barko, J.W., Adams, M.S., and Clesceri, N.L. 1986. Environmental factors and their consideration in the management of submersed aquatic vegetation: a review.

Barnthouse, L.W. 2013. Impacts of entrainment and impingement on fish populations: A review of the scientific evidence. doi:10.1016/j.envsci.2013.03.001.

Barriga, J.P., Espinós, N.A., Chiarello-Sosa, J.M., and Battini, M.A. 2013. The importance of substrate size and interstitial space in the microhabitat selection by the stream-dwelling catfish Hatcheria macraei (Actinopterygii, Trichomycteridae). Hydrobiologia. doi:10.1007/s10750-012-1398-0.

Barton, B.A. 1977. Short-term effects of highway construction on the limnology of a small stream in southern Ontario. Freshw. Biol. doi:10.1111/j.1365-2427.1977.tb01661.x.

Barton, D.R., Taylor, W.D., and Biette, R.M. 1985. Dimensions of Riparian Buffer Strips Required to Maintain Trout Habitat in Southern Ontario Streams. North Am. J. Fish. Manag. doi:10.1577/1548-8659(1985)5<364:dorbsr>2.0.co;2.

Batalla, R.J., and Vericat, D. 2009. Hydrological and sediment transport dynamics of flushing flows: Implications for management in large Mediterranean rivers. River Res. Appl. doi:10.1002/rra.1160.

Beatty, S.J., Morgan, D.L., McAleer, F.J., and Ramsay, A.R. 2010. Groundwater contribution to baseflow maintains habitat connectivity for Tandanus bostocki (Teleostei: Plotosidae) in a south-western Australian river. Ecol. Freshw. Fish. doi:10.1111/j.1600-0633.2010.00440.x.

Bednarek, A.T. 2001. Undamming rivers: A review of the ecological impacts of dam removal. doi:10.1007/s002670010189.

Beechie, T.J., and Sibley, T.H. 1997. Relationships between Channel Characteristics, Woody Debris, and Fish Habitat in Northwestern Washington Streams. Trans. Am. Fish. Soc. doi:10.1577/1548-8659(1997)126<0217:rbccwd>2.3.co;2.

Bettoli, P.W., Maceina, M.J., Noble, R.L., and Betsill, R.K. 1993. Response of a Reservoir Fish Community to Aquatic Vegetation Removal. North Am. J. Fish. Manag. doi:10.1577/1548-8675(1993)013<0110:roarfc>2.3.co;2.

Blackport, R., MacGregor, R., and Imhof, J. 1995. An approach to the management of groundwater resources to protect and enhance fish habitat.

Blann, K.L., Anderson, J.L., Sands, G.R., and Vondracek, B. 2009. Effects of agricultural drainage on aquatic ecosystems: A review. doi:10.1080/10643380801977966.

Bouwes, N., Weber, N., Jordan, C.E., Pollock, M.M., Carl, W., Tattam, I.A., Volk, C., and Wheaton, J.M. 2016. Ecosystem experiment reveals impacts of natural and simulated beaver dams to a threatened population of steelhead (Oncorhynchus mykiss). Nat. Publ. Gr.

Brett, J.R. 1956. Some Principles in the Thermal Requirements of Fishes. Q. Rev. Biol. doi:10.1086/401257.

Bridges, T.S., Ells, S., Hayes, D., Mount, D., Nadeau, S.C., Palermo, M.R., Patmont, C., and Schroeder, P. 2008. The Four Rs of Environmental Dredging: Resuspension, release, residual, and risk. Washington, DC.

Briggs, A.S., and Galarowicz, T.L. 2013. Fish Passage through Culverts in Central Michigan Warmwater Streams. North Am. J. Fish. Manag. **33**(3): 652–664. doi:10.1080/02755947.2013.788589.

Broadmeadow, S.B., Jones, J.G., Langford, T.E.L., Shaw, P.J., and Nisbet, T.R. 2011. The influence of riparian shade on lowland stream water temperatures in southern England and their viability for brown trout. River Res. Appl. doi:10.1002/rra.1354.

Budy, P., Baker, M., and Dahle, S.K. 2011. Predicting fish growth potential and identifying water quality constraints: A spatially-explicit bioenergetics approach. Environ. Manage. **48**(4): 691–709. Springer. doi:10.1007/s00267-011-9717-1.

Bunn, S.E., and Arthington, A.H. 2002. Basic principles and ecological consequences of altered flow regimes for aquatic biodiversity. doi:10.1007/s00267-002-2737-0.

Bunt, C.M., Castro-Santos, T., and Haro, A. 2012. Performance of fish passage structures at upstream barriers to migration. River Res. Appl. **28**: 457–478. doi:10.1002/rra.1565.

Burns, E.S., Armstrong, J., Tang, D., Sakamoto, K., and Lowe, C.G. 2019. The residency, movement patterns and habitat association of several demersal fish species to the Orange County Sanitation District wastewater outfall. Mar. Pollut. Bull. doi:10.1016/j.marpolbul.2019.110638.

Cabaço, S., Santos, R., and Duarte, C.M. 2008, September 10. The impact of sediment burial and erosion on seagrasses: A review. Academic Press. doi:10.1016/j.ecss.2008.04.021.

Carey, R.O., and Migliaccio, K.W. 2009. Contribution of wastewater treatment plant effluents to nutrient dynamics in aquatic systems. doi:10.1007/s00267-009-9309-5.

Carroll, A.G., Przeslawski, R., Duncan, A., Gunning, M., and Bruce, B. 2017. A critical review of the potential impacts of marine seismic surveys on fish & invertebrates. doi:10.1016/j.marpolbul.2016.11.038.

Catalano, M.J., Bozek, M.A., and Pellett, T.D. 2007. Effects of Dam Removal on Fish Assemblage Structure and Spatial Distributions in the Baraboo River, Wisconsin. North Am. J. Fish. Manag. doi:10.1577/m06-001.1.

Causon, P.D., and Gill, A.B. 2018, November 1. Linking ecosystem services with epibenthic biodiversity change following installation of offshore wind farms. Elsevier Ltd. doi:10.1016/j.envsci.2018.08.013.

Chapman, J.M., Proulx, C.L., Veilleux, M.A.N., Levert, C., Bliss, S., André, M.È., Lapointe, N.W.R., and Cooke, S.J. 2014. Clear as mud: A meta-analysis on the effects of sedimentation on freshwater fish and the effectiveness of sediment-control measures. doi:10.1016/j.watres.2014.02.047.

Chessman, B.C., Robinson, D.P., and Hortle, K.G. 1987. Changes in the riffle macroinvertebrate fauna of the Tanjil river, Southeastern Australia, during construction of Blue Rock Dam. Regul. Rivers Res. Manag. doi:10.1002/rrr.3450010404.

Chhor, A.D., Glassman, D.M., Smol, J.P., Vermaire, J.C., and Cooke, S.J. 2020. Ecological consequences of shoreline armoring on littoral fish and benthic macroinvertebrate communities in an Eastern Ontario lake. Aquat. Sci. doi:10.1007/s00027-020-00740-0.

Chiasson, A. 1993. The effect of suspended sediments on ninespine stickleback, Pungitius pungitius, and golden shiner, Notemigonus crysoleucas, in a current of varying velocity. Environ. Biol. Fishes **37**(3): 283–295. doi:10.1007/BF00004635.

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

Clark, C.W., Ellison, W.T., Southall, B.L., Hatch, L., Parijs, S.M. Van, Frankel, A., and Ponirakis, D. 2009. Acoustic masking in marine ecosystems: intuitions, analysis, and implication. Mar. Ecol. Prog. Ser. **395**: 201–222. doi:10.3354/MEPS08402.

Clarke, K.D., Pratt, T.C., Randall, R.G., Dave, A., and Smokorowski, K.E. 2008. Validation of the Flow Management Pathway: Effects of Altered Flow on Fish Habitat and Fishes Downstream from a Hydropower Dam. Canadian Technical Report Fisheries and Aquatic Sciences. 2784: vi + 111p.

Clausen, K.T., Tougaard, J., Carstensen, J., Delefosse, M., and Teilmann, J. 2018. Noise affects porpoise click detections – the magnitude of the effect depends on logger type and detection filter settings. https://doi.org/10.1080/09524622.2018.1477071 **28**(5): 443–458. Taylor & Francis. doi:10.1080/09524622.2018.1477071.

Cloern, J.E. 2001, January 26. Our evolving conceptual model of the coastal eutrophication problem. Inter-Research. doi:10.3354/meps210223.

Collier, T.K., Anulacion, B.F., Arkoosh, M.R., Dietrich, J.P., Incardona, J.P., Johnson, L.L., Ylitalo, G.M., and Myers, M.S. 2013. Effects on Fish of Polycyclic Aromatic HydrocarbonS (PAHS) and Naphthenic Acid Exposures. *In* Fish Physiology. doi:10.1016/B978-0-12-398254-4.00004-2.

Cooper, J.E. 2011. Unionid mussel mortality from habitat loss in the Salmon River, New York, following dam removal. Adv. Environ. Res. **14**: 351–364.

Courtice, G., and Naser, G. 2020. In-stream construction-induced suspended sediment in riverine ecosystems. River Res. Appl. doi:10.1002/rra.3559.

Coutant, C.C. 1977. Cold shock to aquatic organisms: guidance for power-plant siting, design, and operation. Nucl. Saf.

Coutant, C.C., and Whitney, R.R. 2000. Fish Behavior in Relation to Passage through Hydropower Turbines: A Review. Trans. Am. Fish. Soc. doi:10.1577/1548-8659(2000)129<0351:fbirtp>2.0.co;2.

Crane, N.L., and Lashkari, K. 1996. Sound production of gray whales, Eschrichtius robustus , along their migration route: A new approach to signal analysis . J. Acoust. Soc. Am. doi:10.1121/1.416006.

Crispin, V., House, R., and Roberts, D. 1993. Changes in Instream Habitat, Large Woody Debris, and Salmon Habitat after the Restructuring of a Coastal Oregon Stream. North Am. J. Fish. Manag. doi:10.1577/1548-8675(1993)013<0096:ciihlw>2.3.co;2.

Crook, D.A., and Robertson, A.I. 1999. Relationships between riverine fish and woody debris: Implications for lowland rivers. doi:10.1071/MF99072.

Cunjak, R.A. 1996. Winter habitat of selected stream fishes and potential impacts from land-use activity. Can. J. Fish. Aquat. Sci. doi:10.1139/f95-275.

Curry, R.A., Gehrels, J., Noakes, D.L.G., and Swainson, R. 1994. Effects of river flow fluctuations on groundwater discharge through brook trout, Salvelinus fontinalis, spawning and incubation habitats. Hydrobiologia. doi:10.1007/BF00016759.

Cushman, R.M. 1985. Review of Ecological Effects of Rapidly Varying Flows Downstream from Hydroelectric Facilities. North Am. J. Fish. Manag. doi:10.1577/1548-8659(1985)5<330:roeeor>2.0.co;2.

Dahl, P.H., Keith Jenkins, A., Casper, B., Kotecki, S.E., Bowman, V., Boerger, C., Dall'Osto, D.R., Babina, M.A., and Popper, A.N. 2020. Physical effects of sound exposure from underwater explosions on Pacific sardines (Sardinops sagax) . J. Acoust. Soc. Am. doi:10.1121/10.0001064.

Dalen, J., and Knutsen, G.M. 1987. Scaring Effects in Fish and Harmful Effects on Eggs, Larvae and Fry by Offshore Seismic Explorations. *In* Progress in Underwater Acoustics. doi:10.1007/978-1-4613-1871-2_12.

Davies, P.E., and Nelson, M. 1994. Relationships between riparian buffer widths and the effects of logging on stream habitat, invertebrate community composition and fish abundance. Mar. Freshw. Res. doi:10.1071/MF9941289.

Deegan, L.A., Johnson, D.S., Warren, R.S., Peterson, B.J., Fleeger, J.W., Fagherazzi, S., and Wollheim, W.M. 2012. Coastal eutrophication as a driver of salt marsh loss. Nature **490**(7420): 388–392. Nature Publishing Group. doi:10.1038/nature11533.

DFO. 2006. Proceedings of peer review meeting to validate four end points in the pathways of effects diagrams. DFO Can. Sci. Advis. Sec. Proceed. Ser. 2005/031.

DFO. 2013. Framework for Assessing the Ecological Flow Requirements to Support Fisheries in Canada. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2013/017.

DFO. 2014. A science-based framework for assessing the response of fisheries productivity to state of species or habitats. *In* DFO Canadian Scientific Advisory Secretariat Science Advisory Report.

DFO. 2020a. Science Advice for Pathways Of Effects for Marine Shipping In Canada: Biological and Ecological Effects. DFO Can. Sci. Advis. Sec. Sci. Advis. Rep. 2020/030.

DFO. 2020b. Review of the Statement of Canadian Practice with respect to the Mitigation of Seismic Sound in the Marine Environment.

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.

Doeg, T.J., and Koehn, J.D. 1994. Effects of draining and desilting a small weir on downstream fish and macroinvertebrates. Regul. Rivers Res. Manag. doi:10.1002/rrr.3450090407.

Dugan, J.E., Emery, K.A., Alber, M., Alexander, C.R., Byers, J.E., Gehman, A.M., McLenaghan, N., and Sojka, S.E. 2018. Generalizing Ecological Effects of Shoreline Armoring Across Soft Sediment Environments. Estuaries and Coasts **41**(1): 180–196. Springer New York LLC. doi:10.1007/s12237-017-0254-x.

Eliason, E.J., Clark, T.D., Hague, M.J., Hanson, L.M., Gallagher, Z.S., Jeffries, K.M., Gale, M.K., Patterson, D.A., Hinch, S.G., and Farrell, A.P. 2011. Differences in thermal tolerance among sockeye salmon population. Science (80-.). **332**: 109–112.

Erftemeijer, P.L.A., and Robin Lewis, R.R. 2006. Environmental impacts of dredging on seagrasses: A review. Mar. Pollut. Bull. **52**(12): 1553–1572. Pergamon. doi:10.1016/j.marpolbul.2006.09.006.

Evans, W.A. 1980. Fish migration and fish passage: a practical guide to solving fish passage problems. Forest Service, USDA.

Everett, R.A., and Ruiz, G.M. 1993. Coarse woody debris as a refuge from predation in aquatic communities - An experimental test. Oecologia **93**(4): 475–486. Springer-Verlag. doi:10.1007/BF00328954.

Fakan, E.P., and McCormick, M.I. 2019. Boat noise affects the early life history of two damselfishes. Mar. Pollut. Bull. doi:10.1016/j.marpolbul.2019.02.054.

Falke, J.A., Fausch, K.D., Magelky, R., Aldred, A., Durnford, D.S., Riley, L.K., and Oad, R. 2011. The role of groundwater pumping and drought in shaping ecological futures for stream fishes in a dryland river basin of the western Great Plains, USA. Ecohydrology. doi:10.1002/eco.158.

Farrell, A.P., Hinch, S.G., Cooke, S.J., Patterson, D.A., Crossin, G.T., Lapointe, M., and Mathes, M.T. 2008. Pacific salmon in hot water: Applying aerobic scope models and biotelemetry to predict the success of spawning migrations. doi:10.1086/592057.

Faulkner, S.G. 2006. Blasting Effects on Incubating Salmonid Eggs.

Faulkner, S.G., Welz, M., Tonn, W.M., and Schmitt, D.R. 2008. Effects of Simulated Blasting on Mortality of Rainbow Trout Eggs. Trans. Am. Fish. Soc. doi:10.1577/t07-035.1.

Fausch, K.D., and Northcote, T.G. 1992. Large woody debris and salmonid habitat in a small coastal British Columbia stream. Can. J. Fish. Aquat. Sci. doi:10.1139/f92-077.

Fischer, S., and Kummer, H. 2000. Effects of residual flow and habitat fragmentation on distribution and movement of bullhead (Cottus gobio L.) in an alpine stream. *In* Hydrobiologia. doi:10.1007/978-94-011-4164-2_25.

Fleckenstein, J., Anderson, M., Fogg, G., and Mount, J. 2004. Managing Surface Water-Groundwater to Restore Fall Flows in the Cosumnes River. J. Water Resour. Plan. Manag. doi:10.1061/(asce)0733-9496(2004)130:4(301).

Fournet, M.E.H., Matthews, L.P., Gabriele, C.M., Haver, S., Mellinger, D.K., and Klinck, H. 2018. Humpback whales Megaptera novaeangliae alter calling behavior in response to natural sounds and vessel noise. Mar. Ecol. Prog. Ser. doi:10.3354/meps12784.

Fox, G.A., and Wilson, G. V. 2010. The Role of Subsurface Flow in Hillslope and Stream Bank Erosion: A Review. Soil Sci. Soc. Am. J. doi:10.2136/sssaj2009.0319.

Di Franco, E., Pierson, P., Di Iorio, L., Calò, A., Cottalorda, J.M., Derijard, B., Di Franco, A., Galvé, A., Guibbolini, M., Lebrun, J., Micheli, F., Priouzeau, F., Risso-de Faverney, C., Rossi, F., Sabourault, C., Spennato, G., Verrando, P., and Guidetti, P. 2020. Effects of marine noise pollution on Mediterranean fishes and invertebrates: A review. doi:10.1016/j.marpolbul.2020.111450.

Freeman, M.C., Bowen, Z.H., Bovee, K.D., and Irwin, E.R. 2001. Flow and habitat effects on juvenile fish abundance in natural and altered flow regimes. Ecol. Appl. doi:10.1890/1051-0761(2001)011[0179:FAHEOJ]2.0.CO;2.

Fujita, K., Shoji, J., Sugimoto, R., Nakajima, T., Honda, H., Takeuchi, M., Tominaga, O., and Taniguchi, M. 2019. Increase in fish production through bottom-up trophic linkage in coastal waters induced by nutrients supplied via submarine groundwater. Front. Environ. Sci. **7**(JUN): 82. Frontiers Media S.A. doi:10.3389/fenvs.2019.00082.

Gaeta, J.W., Sass, G.G., and Carpenter, S.R. 2014. Drought-driven lake level decline: Effects on coarse woody habitat and fishes. Can. J. Fish. Aquat. Sci. doi:10.1139/cjfas-2013-0451.

Garner, G., Malcolm, I.A., Sadler, J.P., and Hannah, D.M. 2017. The role of riparian vegetation density, channel orientation and water velocity in determining river temperature dynamics. J. Hydrol. doi:10.1016/j.jhydrol.2017.03.024.

Gedan, K.B., Kirwan, M.L., Wolanski, E., Barbier, E.B., and Silliman, B.R. 2011, May 14. The present and future role of coastal wetland vegetation in protecting shorelines: Answering recent challenges to the paradigm. Springer. doi:10.1007/s10584-010-0003-7.

Gervaise, C., Simard, Y., Roy, N., Kinda, B., and Ménard, N. 2012. Shipping noise in whale habitat: Characteristics, sources, budget, and impact on belugas in Saguenay–St. Lawrence Marine Park hub. J. Acoust. Soc. Am. **132**(1): 76. Acoustical Society of AmericaASA. doi:10.1121/1.4728190.

Gill, A.B., and Bartlett, M. 2010. Literature review on the potential effects of electromagnetic fields and subsea noise from marine renewable energy developments on Atlantic salmon, sea trout and European eel.

Girma, M.B., Kifle, D., and Jebessa, H. 2012. Deep underwater seismic explosion experiments and their possible ecological impact - The case of Lake Arenguade - Central Ethiopian highlands. Limnologica. doi:10.1016/j.limno.2011.12.002.

Gorcharoenwat, P., Piyatiratitivorakul, S., and Pengprecha, S. 2015. Effects of temperature and water soluble fraction of palm biodiesel and diesel fuel on hatchability and survival of first stage larvae of macrobrachium rosenbergii. EnvironmentAsia.

Gordon, J., Gillespie, D., Potter, J., Frantzis, A., Simmonds, M.P., Swift, R., and Thompson, D. 2003. A review of the effects of seismic surveys on marine mammals. Mar. Technol. Soc. J. doi:10.4031/002533203787536998.

Govoni, J.J., West, M.A., Settle, L.R., Lynch, R.T., and Greene, M.D. 2008. Effects of underwater explosions on larval fish: Implications for a coastal engineering project. J. Coast. Res. doi:10.2112/05-0518.1.

Grabowski, T.B., and Isely, J.J. 2007. Effects of flow fluctuations on the spawning habitat of a riverine fish. Southeast. Nat. doi:10.1656/1528-7092(2007)6[471:EOFFOT]2.0.CO;2.

Gregor, C.A., and Anderson, T.W. 2016. Relative importance of habitat attributes to predation risk in a temperate reef fish. Environ. Biol. Fishes. doi:10.1007/s10641-016-0496-7.

Griffith, J.S., and Andrews, D.A. 1981. Effects of a Small Suction Dredge on Fishes and Aquatic Invertebrates in Idaho Streams. North Am. J. Fish. Manag. doi:10.1577/1548-8659(1981)1<21:eoassd>2.0.co;2.

Gurnell, A.M., Gregory, K.J., and Petts, G.E. 1995. The role of coarse woody debris in forest aquatic habitats: Implications for management. doi:10.1002/aqc.3270050206.

Halleraker, J.H., Saltveit, S.J., Harby, A., Arnekleiv, J. V., Fjeldstad, H.P., and Kohler, B. 2003. Factors influencing stranding of wild juvenile brown trout (Salmo trutta) during rapid and frequent flow decreases in an artificial stream. River Res. Appl. doi:10.1002/rra.752.

Harmon, M.E., Franklin, J.F., Swanson, F.J., Sollins, P., Gregory, S. V., Lattin, J.D., Anderson, N.H., Cline, S.P., Aumen, N.G., Sedell, J.R., Lienkaemper, G.W., Cromack, K., and Cummins, K.W. 1986. Ecology of Coarse Woody Debris in Temperate Ecosystems. Adv. Ecol. Res. doi:10.1016/S0065-2504(08)60121-X.

Harvey, B.C. 1986. Effects of Suction Gold Dredging on Fish and Invertebrates in Two California Streams. North Am. J. Fish. Manag. **6**(3): 401–409. doi:10.1577/1548-8659(1986)6<401:eosgdo>2.0.co;2.

Harvey, B.C. 1987. Susceptibility of Young-of-the-Year Fishes to Downstream Displacement by Flooding. Trans. Am. Fish. Soc. doi:10.1577/1548-8659(1987)116<851:soyftd>2.0.co;2.

Harvey, B.C., and Lisle, T.E. 1998. Effects of Suction Dredging on Streams: A Review and an Evaluation Strategy. Fisheries **23**(8): 8–17. doi:10.1577/1548-8446(1998)023<0008:eosdos>2.0.co;2.

Hauxwell, J., Cebrián, J., and Valiela, I. 2003. Eelgrass Zostera marina loss in temperate estuaries: Relationship to land-derived nitrogen loads and effect of light limitation imposed by algae. Mar. Ecol. Prog. Ser. **247**: 59–73. Inter-Research. doi:10.3354/meps247059.

Havel, J.E., Kovalenko, K.E., Thomaz, S.M., Amalfitano, S., and Kats, L.B. 2015. Aquatic invasive species: challenges for the future. Hydrobiologia **750**(1): 147–170. doi:10.1007/s10750-014-2166-0.

Hawkins, A.D., and Popper, A.N. 2017. A sound approach to assessing the impact of underwater noise on marine fishes and invertebrates. ICES J. Mar. Sci. doi:10.1093/icesjms/fsw205.

Haxton, T.J., and Findlay, C.S. 2008. Meta-analysis of the impacts of water management on aquatic communities. Can. J. Fish. Aquat. Sci. doi:10.1139/F07-175.

Heifetz, J., Murphy, M.L., and Koski, K. V. 1986. Effects of Logging on Winter Habitat of Juvenile Salmonids in Alaskan Streams. North Am. J. Fish. Manag. doi:10.1577/1548-8659(1986)6<52:eolowh>2.0.co;2.

Heise, R.J., Cope, W.G., Kwak, T.J., and Eads, C.B. 2013. Short-Term Effects of Small Dam Removal on a Freshwater Mussel Assemblage. Freshw. Mollusk Biol. Conserv. **16**(1): 41–52. doi:10.31931/fmbc.v16i1.2013.41-52.

Herb, W.R., Janke, B., Mohseni, O., and Stefan, H.G. 2008. Thermal pollution of streams by runoff from paved surfaces. Hydrol. Process. doi:10.1002/hyp.6986.

Hester, E.T., Doyle, M.W., and Poole, G.C. 2009. The influence of in-stream structures on summer water temperatures via induced hyporheic exchange. Limnol. Oceanogr. doi:10.4319/lo.2009.54.1.0355.

Hicks, A., and Sager, E. 2009. Aquatic Plants Guide: Aquatic plants in the Kawartha Lakes – their growth, importance and management. Available from http://www.lakefieldherald.com/KLSA/Plant_Guide_web.pdf.

Hobbs, R.J. 2000. Land-use changes and invasions. *In* Invasive species in a changing world.

Houser, D.L., and Pruess, H. 2009. The effects of construction on water quality: A case study of the culverting of Abram Creek. Environ. Monit. Assess. doi:10.1007/s10661-008-0445-9.

Hutchison, Z.L., Gill, A.B., Sigray, P., He, H., and King, J.W. 2020. Anthropogenic electromagnetic fields (EMF) influence the behaviour of bottom-dwelling marine species. Sci. Rep. **10**(1): 1–15. Nature Research. doi:10.1038/s41598-020-60793-x.

Intamat, S., Phoonaploy, U., Sriuttha, M., Tengjaroenkul, B., and Neeratanaphan, L. 2016. Heavy metal accumulation in aquatic animals around the gold mine area of Loei province, Thailand. Hum. Ecol. Risk Assess. doi:10.1080/10807039.2016.1187062.

Irvine, R.L., Thorley, J.L., Westcott, R., Schmidt, D., and Derosa, D. 2015. Why do fish strand? An analysis of ten years of flow reduction monitoring data from the Columbia and Kootenay rivers, Canada. River Res. Appl. doi:10.1002/rra.2823.

James, W.F., Barko, J.W., and Eakin, H.L. 2004. Impacts of sediment dewatering and rehydration on sediment nitrogen concentration and macrophyte growth. Can. J. Fish. Aquat. Sci. doi:10.1139/f04-018.

Jones, M.J., and Hale, R. 2020. Using knowledge of behaviour and optic physiology to improve fish passage through culverts. Fish Fish. **21**(3): 557–569. doi:10.1111/faf.12446.

Jurcak, A.M., Gauthier, S.J., and Moore, P.A. 2015. The Effects of Biodiesel and Crude Oil on the Foraging Behavior of Rusty Crayfish, Orconectes rusticus. Arch. Environ. Contam. Toxicol. doi:10.1007/s00244-015-0181-4.

Kahler, T.H., and Quinn, T.P. 1998. Juvenile and resident salmonid movement and passage through culverts. Washington State Transportation Center,Final Research Report, Research Project T9903, Task 96. Seattle, WA: University of Washington, 38 pp. (1998).

Katopodis, C. 2005. Developing a toolkit for fish passage, ecological flow management and fish habitat works. doi:10.1080/00221680509500144.

Keery, J., Binley, A., Crook, N., and Smith, J.W.N. 2007. Temporal and spatial variability of groundwater-surface water fluxes: Development and application of an analytical method using temperature time series. J. Hydrol. doi:10.1016/j.jhydrol.2006.12.003.

Keevin, T.M. 1998. A review of natural resource agency recommendations for mitigating the impacts of underwater blasting. doi:10.1080/10641269891314302.

Kemp, P., Sear, D., Collins, A., Naden, P., and Jones, I. 2011. The impacts of fine sediment on riverine fish. Hydrol. Process. doi:10.1002/hyp.7940.

Kemp, P.S. 2015. Impoundments, barriers and abstractions. *In* Freshwater Fisheries Ecology. doi:10.1002/9781118394380.ch52.

Kemp, P.S., and O'Hanley, J.R. 2010. Procedures for evaluating and prioritising the removal of fish passage barriers: A synthesis. doi:10.1111/j.1365-2400.2010.00751.x.

Khan, N., Warith, M.A., and Luk, G. 2007. A Comparison of acute toxicity of biodiesel, biodiesel blends, and diesel on aquatic organisms. J. Air Waste Manag. Assoc. doi:10.1080/10473289.2007.10465333.

Kinouchi, T., Yagi, H., and Miyamoto, M. 2007. Increase in stream temperature related to anthropogenic heat input from urban wastewater. J. Hydrol. doi:10.1016/j.jhydrol.2006.11.002.

Klemperer, S.L., and Cash, M.D. 2007. Temporal geochemical variation in Ethiopian Lakes Shala, Arenguade, Awasa, and Beseka: Possible environmental impacts from underwater and borehole detonations. J. African Earth Sci. doi:10.1016/j.jafrearsci.2006.10.006.

Kovalenko, K.E., Thomaz, S.M., and Warfe, D.M. 2012. Habitat complexity: Approaches and future directions. Hydrobiologia. doi:10.1007/s10750-011-0974-z.

Krzeminska, D., Kerkhof, T., Skaalsveen, K., and Stolte, J. 2019. Effect of riparian vegetation on stream bank stability in small agricultural catchments. Catena. doi:10.1016/j.catena.2018.08.014.

Larson, L.L., and Larson, S.L. 1996. Riparian shade and stream temperature: A perspective.

Laubel, A., Kronvang, B., Hald, A.B., and Jensen, C. 2003. Hydromorphological and biological factors influencing sediment and phosphorus loss via bank erosion in small lowland rural streams in Denmark. Hydrol. Process. doi:10.1002/hyp.1302.

Lemasson, B.H., Haefner, J.W., and Bowen, M.D. 2008. The effect of avoidance behavior on predicting fish passage rates through water diversion structures. Ecol. Modell. doi:10.1016/j.ecolmodel.2008.08.013.

Lévesque, L.M., and Dubé, M.G. 2007. Review of the effects of in-stream pipeline crossing construction on aquatic ecosystems and examination of Canadian methodologies for impact assessment. doi:10.1007/s10661-006-9542-9.

Liebig, H., Céréghino, R., Puy, L., Belaud, A., and Sovan, L. 1999. Impact of hydropeaking on the abundance of juvenile brown trout in a Pyrenean stream. Arch. fur Hydrobiol. doi:10.1127/archiv-hydrobiol/144/1999/439.

Likens, G.E., and Bormann, F.H. 1974. Linkages between terrestrial and aquatic ecosystems. Bioscience. doi:10.2307/1296852.

Løkkeborg, S., Ona, E., Vold, A., and Salthaug, A. 2012. Sounds from seismic air guns: Gear- and speciesspecific effects on catch rates and fish distribution. Can. J. Fish. Aquat. Sci. doi:10.1139/F2012-059.

Lokteff, R.L., Roper, B.B., and Wheaton, J.M. 2013. Do beaver dams impede the movement of trout? Trans. Am. Fish. Soc. doi:10.1080/00028487.2013.797497.

Lozano, N., Rice, C.P., Pagano, J., Zintek, L., Barber, L.B., Murphy, E.W., Nettesheim, T., Minarik, T., and Schoenfuss, H.L. 2012. Concentration of organic contaminants in fish and their biological effects in a wastewater-dominated urban stream. Sci. Total Environ. doi:10.1016/j.scitotenv.2011.12.059.

MacLean, K., Prystay, T.S., Lawrence, M.J., Zolderdo, A.J., Gutowsky, L.F.G., Staaterman, E., Gallagher, A.J., and Cooke, S.J. 2020. Going the Distance: Influence of Distance Between Boat Noise and Nest Site on the Behavior of Paternal Smallmouth Bass. Water. Air. Soil Pollut. doi:10.1007/s11270-020-04470-9.

Macura, B., Byström, P., Airoldi, L., Eriksson, B.K., Rudstam, L., and Støttrup, J.G. 2019. Impact of structural habitat modifications in coastal temperate systems on fish recruitment: A systematic review. doi:10.1186/s13750-019-0157-3.

Magirl, C.S., Hilldale, R.C., Curran, C.A., Duda, J.J., Straub, T.D., Domanski, M., and Foreman, J.R. 2015. Large-scale dam removal on the Elwha River, Washington, USA: Fluvial sediment load. Geomorphology. doi:10.1016/j.geomorph.2014.12.032.

Majerova, M., Neilson, B.T., Schmadel, N.M., Wheaton, J.M., and Snow, C.J. 2015. Impacts of beaver dams on hydrologic and temperature regimes in a mountain stream. Hydrol. Earth Syst. Sci. doi:10.5194/hess-19-3541-2015.

Malk, V., Barreto Tejera, E., Simpanen, S., Dahl, M., Mäkelä, R., Häkkinen, J., Kiiski, A., and Penttinen, O.P. 2014. NAPL migration and ecotoxicity of conventional and renewable fuels in accidental spill scenarios. Environ. Sci. Pollut. Res. doi:10.1007/s11356-014-2851-6.

Martin, S.B., Lucke, K., and Barclay, D.R. 2020. Techniques for distinguishing between impulsive and non-impulsive sound in the context of regulating sound exposure for marine mammals. J. Acoust. Soc. Am. **147**(4): 2159–2176. Acoustical Society of America (ASA). doi:10.1121/10.0000971.

Mason, K., and Metikosh, S. 2007. Pathways of Effects Literature Review: Temperature and Dissolved Oxygen Endpoints. *In* DFO Can. Sci. Advis. Sec. Res. Doc.

Maxwell, R.J., Zolderdo, A.J., de Bruijn, R., Brownscombe, J.W., Staaterman, E., Gallagher, A.J., and Cooke, S.J. 2018. Does motor noise from recreational boats alter parental care behaviour of a nesting freshwater fish? Aquat. Conserv. Mar. Freshw. Ecosyst. doi:10.1002/aqc.2915.

McCallum, E.S., Nikel, K.E., Mehdi, H., Du, S.N.N., Bowman, J.E., Midwood, J.D., Kidd, K.A., Scott, G.R., and Balshine, S. 2019. Municipal wastewater effluent affects fish communities: A multi-year study involving two wastewater treatment plants. Environ. Pollut. doi:10.1016/j.envpol.2019.06.075.

McCarthy, E. 2007. International regulation of underwater sound: establishing rules and standards to address ocean noise pollution. Springer Science & Business Media.

McCauley, R.D., Fewtrell, J., Duncan, A.J., Jenner, C., Jenner, M.-N., Penrose, J.D., Prince, R.I.T., Adhitya, A., Murdoch, J., and McCabe, K. 2000. MARINE SEISMIC SURVEYS— A STUDY OF ENVIRONMENTAL IMPLICATIONS. APPEA J. doi:10.1071/aj99048.

McCauley, R.D., Fewtrell, J., and Popper, A.N. 2003. High intensity anthropogenic sound damages fish ears. J. Acoust. Soc. Am. doi:10.1121/1.1527962.

McKinley, A., and Johnston, E.L. 2010. Impacts of contaminant sources on marine fish abundance and species richness: A review and meta-analysis of evidence from the field. Mar. Ecol. Prog. Ser. doi:10.3354/meps08856.

Mclaughlin, R.L., Smyth, E.R.B., Castro-Santos, T., Jones, M.L., Koops, M.A., Pratt, T.C., and Vélez-Espino, L.A. 2013. Unintended consequences and trade-offs of fish passage. Fish Fish. **14**(4): 580–604. doi:10.1111/faf.12003.

Meador, M.R., and Goldstein, R.M. 2003. Assessing water quality at large geographic scales: Relations among land use, water physicochemistry, riparian condition, and fish community structure. Environ. Manage. **31**(4): 504–517. Springer. doi:10.1007/s00267-002-2805-5.

Mehdi, H., Lau, S.C., Synyshyn, C., Salena, M.G., McCallum, E.S., Muzzatti, M.N., Bowman, J.E., Mataya, K., Bragg, L.M., Servos, M.R., Kidd, K.A., Scott, G.R., and Balshine, S. 2021. Municipal wastewater as an ecological trap: Effects on fish communities across seasons. Sci. Total Environ. doi:10.1016/j.scitotenv.2020.143430.

Meier, W., Bonjour, C., Wüest, A., and Reichert, P. 2003. Modeling the Effect of Water Diversion on the Temperature of Mountain Streams. J. Environ. Eng. **129**(8): 755–764. American Society of Civil Engineers (ASCE). doi:10.1061/(asce)0733-9372(2003)129:8(755).

Mercaldo-Allen, R., and Goldberg, R. 2011. Review of the Ecological Effects of Dredging in the Cultivation and Harvest of Molluscan Shellfish. NOAA Tech Memo NMFS-NE-220.

Midwood, J.D., and Chow-Fraser, P. 2012. Changes in aquatic vegetation and fish communities following 5 years of sustained low water levels in coastal marshes of eastern Georgian Bay, Lake Huron. Glob. Chang. Biol. doi:10.1111/j.1365-2486.2011.02558.x.

Minns, C.K., Randall, R.G., Smokorowski, K.E., Clarke, K.D., Vélez-Espino, A., Gregory, R.S., Courtenay, S., and LeBlanc, P. 2011. Direct and indirect estimates of the productive capacity of fish habitat under Canada’s Policy for the Management of Fish Habitat: Where have we been, where are we now, and where are we going? doi:10.1139/F2011-130.

Monirul Qader Mirza, M. 2006. The Ganges Water Diversion: Environmental Effects and Implications - An Introduction. *In* The Ganges Water Diversion: Environmental Effects and Implications. doi:10.1007/1-4020-2480-0_1.

Montgomery, J.C., Jeffs, A., Simpson, S.D., Meekan, M., and Tindle, C. 2006. Sound as an Orientation Cue for the Pelagic Larvae of Reef Fishes and Decapod Crustaceans. doi:10.1016/S0065-2881(06)51003-X.

Moyle, P.B., and Israel, J.A. 2005. Untested assumptions: Effectiveness of screening diversions for conservation of fish populations. Fisheries. doi:10.1577/1548-8446(2005)30[20:UA]2.0.CO;2.

Mueller-Blenkle, C., Mcgregor, P.K., Gill, A.B., Andersson, M.H., Metcalfe, J., Bendall, V., Sigray, P., Wood, D., and Thomsen, F. 2010. EFFECTS OF PILE-DRIVING NOISE ON THE BEHAVIOUR OF MARINE FISH. *In* Design.

Munsch, S.H., Cordell, J.R., and Toft, J.D. 2017, October 1. Effects of shoreline armouring and overwater structures on coastal and estuarine fish: opportunities for habitat improvement. Blackwell Publishing Ltd. doi:10.1111/1365-2664.12906.

Murphy, M.L., and Koski, K. V. 1989. Input and Depletion of Woody Debris in Alaska Streams and Implications for Streamside Management. North Am. J. Fish. Manag. doi:10.1577/1548-8675(1989)009<0427:iadowd>2.3.co;2.

Myers, M.J., and Resh, V.H. 2000. Undercut Banks: A Habitat for More Than Just Trout. Trans. Am. Fish. Soc. doi:10.1577/1548-8659(2000)129<0594:ubahfm>2.0.co;2.

Nagrodski, A., Raby, G.D., Hasler, C.T., Taylor, M.K., and Cooke, S.J. 2012. Fish stranding in freshwater systems: Sources, consequences, and mitigation. J. Environ. Manage. doi:10.1016/j.jenvman.2012.03.007.

Nathan, R., Getz, W.M., Revilla, E., Holyoak, M., Kadmon, R., Saltz, D., and Smouse, P.E. 2008. A movement ecology paradigm for unifying organismal movement research. Proc. Natl. Acad. Sci. **105**(49): 19052–19059. doi:10.1073/pnas.0800375105.

Nedelec, S.L., Campbell, J., Radford, A.N., Simpson, S.D., and Merchant, N.D. 2016. Particle motion: the missing link in underwater acoustic ecology. Methods Ecol. Evol. doi:10.1111/2041-210X.12544.

Newcombe, C.P., and Jensen, J.O.T. 1996. Channel Suspended Sediment and Fisheries: A Synthesis for Quantitative Assessment of Risk and Impact. North Am. J. Fish. Manag. doi:10.1577/1548-8675(1996)016<0693:cssafa>2.3.co;2.

Nielsen, M.H., Bach, L., and Bollwerk, S.M. 2015. Spreading of sediment due to underwater blasting and dredging: Field observations from quay construction in Sisimiut, Greenland. Ocean Coast. Manag. doi:10.1016/j.ocecoaman.2015.09.012.

Niimi, A.J. 1983. Biological and toxicological effects of environmental contaminants in fish and their eggs. Can. J. Fish. Aquat. Sci. doi:10.1139/f83-045.

Nowacek, D.P., Thorne, L.H., Johnston, D.W., and Tyack, P.L. 2007. Responses of cetaceans to anthropogenic noise. doi:10.1111/j.1365-2907.2007.00104.x.

Nowak, P., Kucharska, K., and Kamiński, M. 2019. Ecological and health effects of lubricant oils emitted into the environment. doi:10.3390/ijerph16163002.

O’Hanley, J.R., and Tomberlin, D. 2005. Optimizing the removal of small fish passage barriers. Environ. Model. Assess. doi:10.1007/s10666-004-4268-y.

Öhman, M.C., Sigray, P., and Westerberg, H. 2007. Offshore Windmills and the Effects of Electromagnetic Fields on Fish.

Parks, S.E., Cusano, D.A., Bocconcelli, A., Friedlaender, A.S., and Wiley, D.N. 2016. Noise impacts on social sound production by foraging humpback whales. *In* Proceedings of Meetings on Acoustics. doi:10.1121/2.0000247.

Peake, S.J. 2008. Swimming performance and behavior of fish species endemic to Newfoundland and Labrador: A literature review for the purpose of establishing design and water velocity criteria for fishways and culverts. Can. J. Fish. Aquat. Sci. **2843**(2843): v + 52p.

Perkin, J.S., Gido, K.B., Falke, J.A., Fausch, K.D., Crockett, H., Johnson, E.R., Sanderson, J., and Turner, B.L. 2017. Groundwater declines are linked to changes in Great Plains stream fish assemblages. Proc. Natl. Acad. Sci. U. S. A. doi:10.1073/pnas.1618936114.

Popper, A.N., and Hastings, M.C. 2009. The effects of anthropogenic sources of sound on fishes. doi:10.1111/j.1095-8649.2009.02319.x.

Popper, A.N., and Hawkins, A.D. 2019. An overview of fish bioacoustics and the impacts of anthropogenic sounds on fishes. doi:10.1111/jfb.13948.

Popper, A.N., Hawkins, A.D., and Thomsen, F. 2020. Taking the Animals’ Perspective Regarding Anthropogenic Underwater Sound. doi:10.1016/j.tree.2020.05.002.

Power, G., Brown, R.S., and Imhof, J.G. 1999. Groundwater and fish - Insights from northern North America. Hydrol. Process. doi:10.1002/(SICI)1099-1085(19990228)13:3<401::AID-HYP746>3.0.CO;2-A.

Power, M.E., Dietrich, W.E., and Finlay, J.C. 1996. Dams and downstream aquatic biodiversity: Potential food web consequences of hydrologic and geomorphic change. *In* Environmental Management. doi:10.1007/BF01205969.

Pusey, B.J., and Arthington, A.H. 2003. Importance of the riparian zone to the conservation and management of freshwater fish: A review. doi:10.1071/MF02041.

Putland, R.L., and Mensinger, A.F. 2019. Acoustic deterrents to manage fish populations. doi:10.1007/s11160-019-09583-x.

Qin, J., Cheng, F., Zhang, L., Schmidt, B.V., Liu, J., and Xie, S. 2019. Invasions of two estuarine gobiid species interactively induced from water diversion and saltwater intrusion. Manag. Biol. Invasions. doi:10.3391/MBI.2019.10.1.09.

Quiros, T.E.A.L., Croll, D., Tershy, B., Fortes, M.D., and Raimondi, P. 2017. Land use is a better predictor of tropical seagrass condition than marine protection. Biol. Conserv. **209**: 454–463. Elsevier Ltd. doi:10.1016/j.biocon.2017.03.011.

Raabe, J.K., and Hightower, J.E. 2014. Assessing Distribution of Migratory Fishes and Connectivity following Complete and Partial Dam Removals in a North Carolina River. North Am. J. Fish. Manag. **34**(5): 955–969. doi:10.1080/02755947.2014.938140.

Radford, A.N., Kerridge, E., and Simpson, S.D. 2014. Acoustic communication in a noisy world: Can fish compete with anthropogenic noise? doi:10.1093/beheco/aru029.

Randall, R.G., and Minns, C.K. 2002. Comparison of a Habitat Productivity Index (HPI) and an Index of Biotic Integrity (IBI) for measuring the productive capacity of fish habitat in nearshore areas of the Great Lakes. J. Great Lakes Res. doi:10.1016/S0380-1330(02)70580-7.

Randle, T.J., Bountry, J.A., Ritchie, A., and Wille, K. 2015. Large-scale dam removal on the Elwha River, Washington, USA: Erosion of reservoir sediment. Geomorphology. doi:10.1016/j.geomorph.2014.12.045.

Reid, S.M., Ade, F., and Metikosh, S. 2004. Sediment entrainment during pipeline water crossing construction: predictive models and crossing method comparison. J. Environ. Eng. Sci. **3**(2): 81–88. doi:10.1139/s03-064.

Reid, S.M., and Anderson, P.G. 1999. Effects of sediment released during open-cut pipeline water crossings. Can. Water Resour. J. **24**(3): 235–251. doi:10.4296/cwrj2403235.

Reid, S.M., Isaac, G., Metikosh, S., and Evans, J. 2003. Physiological response of rainbow trout to sediment released during open-cut pipeline water crossing construction. Water Qual. Res. J. Canada **38**(3): 473–481. doi:10.2166/wqrj.2003.030.

Reid, S.M., Stoklosar, S., Metikosh, S., and Evans, J. 2002. Effectiveness of isolated pipeline crossing techniques to mitigate sediment impacts on brook trout streams. Water Qual. Res. J. Canada **37**(2): 473–488. doi:10.2166/wqrj.2002.031.

Robertson, M.., Scruton, D.., Gregory, R.., and Clarke, K.. 2006. Effect of suspended sediment on freshwater fish and fish habitat.

Rolls, R.J., Leigh, C., and Sheldon, F. 2012. Mechanistic effects of low-flow hydrology on riverine ecosystems: Ecological principles and consequences of alteration. Freshw. Sci. doi:10.1899/12-002.1.

Rozas, L.P., and Odum, W.E. 1988. Occupation of submerged aquatic vegetation by fishes. Test. Roles Food Refug.

Rusak, J.A., and Mosindy, T. 1997. Seasonal movements of lake sturgeon in Lake of the Woods and the Rainy River, Ontario. Can. J. Zool. doi:10.1139/z97-048.

Rytwinski, T., Algera, D.A., Taylor, J.J., Smokorowski, K.E., Bennett, J.R., Harrison, P.M., and Cooke, S.J. 2017. What are the consequences of fish entrainment and impingement associated with hydroelectric dams on fish productivity? A systematic review protocol. Environ. Evid. **6**(1): 1–9. BioMed Central. doi:10.1186/s13750-017-0087-x.

Sass, G.G., Shaw, S.L., Rooney, T.P., Rypel, A.L., Raabe, J.K., Smith, Q.C., Hrabik, T.R., and Toshner, S.T. 2019. Coarse woody habitat and glacial lake fisheries in the Midwestern United States: knowns, unknowns, and an experiment to advance our knowledge. Lake Reserv. Manag. doi:10.1080/10402381.2019.1630530.

Schlacher, T.A., Mondon, J.A., and Connolly, R.M. 2007. Estuarine fish health assessment: Evidence of wastewater impacts based on nitrogen isotopes and histopathology. Mar. Pollut. Bull. doi:10.1016/j.marpolbul.2007.07.014.

Schreck, C.B. 2009. Accumulation and long-term effects of stress in fish. *In* The biology of animal stress: basic principles and implications for animal welfare. doi:10.1079/9780851993591.0147.

Seilheimer, T.S., Wei, A., Chow-Fraser, P., and Eyles, N. 2007. Impact of urbanization on the water quality, fish habitat, and fish community of a Lake Ontario marsh, Frenchman’s Bay. Urban Ecosyst. **10**(3): 299–319. Springer. doi:10.1007/s11252-007-0028-5.

Sethi, S.A., Selle, A.R., Doyle, M.W., Stanley, E.H., and Kitchel, H.E. 2004. Response of Unionid Mussels to Dam Removal in Koshkonong Creek, Wisconsin (USA). Hydrobiologia **525**(1–3): 157–165. doi:10.1023/B:HYDR.0000038862.63229.56.

Shen, Y., and Diplas, P. 2010. Modeling Unsteady Flow Characteristics of Hydropeaking Operations and Their Implications on Fish Habitat. J. Hydraul. Eng. doi:10.1061/(asce)hy.1943-7900.0000112.

Shields, F.D., Knight, S.S., and Cooper, C.M. 1994. Effects of channel incision on base flow stream habitats and fishes. Environ. Manage. doi:10.1007/BF02393749.

Sierra-Flores, R., Atack, T., Migaud, H., and Davie, A. 2015. Stress response to anthropogenic noise in Atlantic cod Gadus morhua L. Aquac. Eng. doi:10.1016/j.aquaeng.2015.06.003.

Simpson, S.D., Radford, A.N., Nedelec, S.L., Ferrari, M.C.O., Chivers, D.P., McCormick, M.I., and Meekan, M.G. 2016. Anthropogenic noise increases fish mortality by predation. Nat. Commun. doi:10.1038/ncomms10544.

Slabbekoorn, H., Bouton, N., van Opzeeland, I., Coers, A., ten Cate, C., and Popper, A.N. 2010. A noisy spring: The impact of globally rising underwater sound levels on fish. doi:10.1016/j.tree.2010.04.005.

Smokorowski, K.E., and Pratt, T.C. 2007. Effect of a change in physical structure and cover on fish and fish habitat in freshwater ecosystems- A review and meta-analysis. Environ. Rev. **15**: 15–41. doi:10.1139/a06-007.

Solomon, K.R., Dalhoff, K., Volz, D., and Van Der Kraak, G. 2013. Effects of Herbicides on Fish. *In* Fish Physiology. doi:10.1016/B978-0-12-398254-4.00007-8.

de Soto, N.A. 2016. Peer-reviewed studies on the effects of anthropogenic noise on marine invertebrates: From scallop larvae to giant squid. *In* Advances in Experimental Medicine and Biology. doi:10.1007/978-1-4939-2981-8_3.

De Soto, N.A., Delorme, N., Atkins, J., Howard, S., Williams, J., and Johnson, M. 2013. Anthropogenic noise causes body malformations and delays development in marine larvae. Sci. Rep. doi:10.1038/srep02831.

Stanley, E.H., and Doyle, M.W. 2003. Trading off: The Ecological Effects of Dam Removal. Front. Ecol. Environ. **1**(1): 15. doi:10.2307/3867960.

Stanley, J.A., Radford, C.A., and Jeffs, A.G. 2012. Effects of underwater noise on larval settlement. Adv. Exp. Med. Biol. doi:10.1007/978-1-4419-7311-5_84.

Steele, R.J., and Smokorowski, K.E. 2000. Review of literature related to the downstream ecological effects of hydroelectric power generation. *In* Canadian Technical Report of Fisheries and Aquatic Sciences.

Stone, M. 2000. The role of erosion and sediment transport in nutrient and contaminant transfer. International Association of Hydrological Sciences.

Stromberg, J.C., Lite, S.J., Marler, R., Paradzick, C., Shafroth, P.B., Shorrock, D., White, J.M., and White, M.S. 2007. Altered stream-flow regimes and invasive plant species: The Tamarix case. Glob. Ecol. Biogeogr. doi:10.1111/j.1466-8238.2007.00297.x.

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. doi:10.1016/j.scitotenv.2008.04.055.

Szekeres, P., Eliason, E., Lapointe, D., Donaldson, M., Brownscombe, J., and Cooke, S. 2016. On the neglected cold side of climate change and what it means to fish. Clim. Res. **69**(3): 239–245. doi:10.3354/cr01404.

Tabacchi, E., Correll, D.L., Hauer, R., Pinay, G., Planty-Tabacchi, A.M., and Wissmar, R.C. 1998. Development, maintenance and role of riparian vegetation in the river landscape. Freshw. Biol. doi:10.1046/j.1365-2427.1998.00381.x.

Tabacchi, E., Lambs, L., Guilloy, H., Planty-Tabacchi, A.M., Muller, E., and Décamps, H. 2000. Impacts of riparian vegetation on hydrological processes. Hydrol. Process. doi:10.1002/1099-1085(200011/12)14:16/17<2959::AID-HYP129>3.0.CO;2-B.

Tank, J.L., Rosi-Marshall, E.J., Griffiths, N.A., Entrekin, S.A., and Stephen, M.L. 2010. A review of allochthonous organic matter dynamics and metabolism in streams. doi:10.1899/08-170.1.

Taormina, B., Bald, J., Want, A., Thouzeau, G., Lejart, M., Desroy, N., and Carlier, A. 2018, November 1. A review of potential impacts of submarine power cables on the marine environment: Knowledge gaps, recommendations and future directions. Elsevier Ltd. doi:10.1016/j.rser.2018.07.026.

Taylor, K.G., and Owens, P.N. 2009. Sediments in urban river basins: A review of sediment-contaminant dynamics in an environmental system conditioned by human activities. doi:10.1007/s11368-009-0103-z.

Teleki, G.C., and Chamberlain, A.J. 1978. Acute Effects of Underwater Construction Blasting on Fishes in Long Point Bay, Lake Erie. J. Fish. Res. Board Canada. doi:10.1139/f78-190.

Tetreault, G.R., Brown, C.J.M., Bennett, C.J., Oakes, K.D., McMaster, M.E., and Servos, M.R. 2013. Fish community responses to multiple municipal wastewater inputs in a watershed. Integr. Environ. Assess. Manag. doi:10.1002/ieam.1364.

Theurer, F.D., Lines, I., and Nelson, T. 1985. INTERACTION BETWEEN RIPARIAN VEGETATION, WATER TEMPERATURE, AND SALMONID HABITAT IN THE TUCANNON RIVER. JAWRA J. Am. Water Resour. Assoc. doi:10.1111/j.1752-1688.1985.tb05351.x.

Thévenet, A., and Statzner, B. 1999. Linking fluvial fish community to physical habitat in large woody debris: Sampling effort, accuracy and precision. Arch. fur Hydrobiol. doi:10.1127/archiv-hydrobiol/145/1999/57.

Tiemann, J.S. 2004. Short-term effects of logging and bridge construction on habitat of two Kansas intermittent streams. Trans. Kansas Acad. Sci. doi:10.1660/0022-8443(2004)107[0136:seolab]2.0.co;2.

Tiemann, J.S., Stodola, A.P., and Vinsel, R.M. 2018. Danville Dam 2018 Salvage Report: Results of the fish and freshwater mussel surveys following the removal of the Danville Dam on the Vermilion River. Springfield, IL.

Tornabene, B.J., Smith, T.W., Tews, A.E., Beattie, R.P., Gardner, W.M., and Eby, L.A. 2020. Trends in River Discharge and Water Temperature Cue Spawning Movements of Blue Sucker, Cycleptus elongatus, in an Impounded Great Plains River. Copeia. doi:10.1643/CI-19-256.

Tricas, T., and Gill., A. 2011. Effects of EMFs from Undersea Power Cables on Elasmobranchs and Other Marine Species.

Tsui, P.T.P., and McCart, P.J. 1981. Effects of stream-crossing by a pipeline on the benthic macroinvertebrate communities of a small mountain stream. Hydrobiologia **79**(3): 271–276. doi:10.1007/BF00006324.

Vajda, Alan, M., Barber, L.B., Gray, J.L., Lopez, E.M., Woodling, J.D., and Norris, D.O. 2008. Reproductive disruption in fish downstream from an estrogenic wastewater effluent. Environ. Sci. Technol. doi:10.1021/es0720661.

Valiela, I., and Cole, M.L. 2002. Comparative evidence that salt marshes and mangroves may protect seagrass meadows from land-derived nitrogen loads. Ecosystems **5**(1): 92–102. Springer. doi:10.1007/s10021-001-0058-4.

Valiela, I., Costa, J., Foreman, K., Teal, J.M., Howes, B., and Aubrey, D. 1990. Transport of groundwater-borne nutrients from watersheds and their effects on coastal waters. Biogeochemistry **10**(3): 177–197. Kluwer Academic Publishers. doi:10.1007/BF00003143.

Valley, R., Cross, T., and Radomski, P.J. 2004. The Role of Submersed Aquatic Vegetation as Habitat for Fish in Minnesota Lakes, Including the Implications of Non-native Plant Invasions and their Management Lead in Sport Fishing Tackle Policy View project Water Level Regulations on MN-Ontario border waters View project. Available from https://www.researchgate.net/publication/237653258 [accessed 4 May 2021].

Vitule, J.R.S., Skóra, F., and Abilhoa, V. 2012. Homogenization of freshwater fish faunas after the elimination of a natural barrier by a dam in Neotropics. Divers. Distrib. **18**(2): 111–120. doi:10.1111/j.1472-4642.2011.00821.x.

Vlotman, W.F., Smedema, L.K., and Rycroft., D.W. 2020. Modern land drainage: Planning, design and management of agricultural drainage systems. CRC Press.

Waco, K.E., and Taylor, W.W. 2010. The influence of groundwater withdrawal and land use changes on brook charr (Salvelinus fontinalis) thermal habitat in two coldwater tributaries in Michigan, U.S.A. Hydrobiologia. doi:10.1007/s10750-010-0204-0.

Walsh, C.J., Roy, A.H., Feminella, J.W., Cottingham, P.D., Groffman, P.M., and Morgan, R.P. 2005. The urban stream syndrome: Current knowledge and the search for a cure. *In* Journal of the North American Benthological Society. doi:10.1899/04-028.1.

Wang, C., Zheng, S.S., Wang, P.F., and Hou, J. 2015. Interactions between vegetation, water flow and sediment transport: A review. doi:10.1016/S1001-6058(15)60453-X.

Wang, Q., Kim, D., Dionysiou, D.D., Sorial, G.A., and Timberlake, D. 2004. Sources and remediation for mercury contamination in aquatic systems - A literature review. Environ. Pollut. doi:10.1016/j.envpol.2004.01.010.

Warren, M.L., and Pardew, M.G. 1998. Road Crossings as Barriers to Small-Stream Fish Movement. Trans. Am. Fish. Soc. doi:10.1577/1548-8659(1998)127<0637:rcabts>2.0.co;2.

Weber, N., Bouwes, N., Pollock, M.M., Volk, C., Wheaton, J.M., Wathen, G., Wirtz, J., and Jordan, C.E. 2017. Alteration of stream temperature by natural and artificial beaver dams. PLoS One. doi:10.1371/journal.pone.0176313.

Weilgart, L.S. 2007. The impacts of anthropogenic ocean noise on cetaceans and implications for management. doi:10.1139/Z07-101.

Weisberg, S.B., and Burton, W.H. 1993. Enhancement of Fish Feeding and Growth after an Increase in Minimum Flow below the Conowingo Dam. North Am. J. Fish. Manag. doi:10.1577/1548-8675(1993)013<0103:eoffag>2.3.co;2.

Wenger, A.S., Harvey, E., Wilson, S., Rawson, C., Newman, S.J., Clarke, D., Saunders, B.J., Browne, N., Travers, M.J., Mcilwain, J.L., Erftemeijer, P.L.A., Hobbs, J.P.A., Mclean, D., Depczynski, M., and Evans, R.D. 2017. A critical analysis of the direct effects of dredging on fish. Fish Fish. **18**(5): 967–985. doi:10.1111/faf.12218.

Westerberg, H., and Lagenfelt, I. 2008. Sub-sea power cables and the migration behaviour of the European eel. Fish. Manag. Ecol. **15**(5–6): 369–375. John Wiley & Sons, Ltd. doi:10.1111/j.1365-2400.2008.00630.x.

Wichert, G.A., and Rapport, D.J. 1998. Fish community structure as a measure of degradation and rehabilitation of riparian systems in an agricultural drainage basin. Environ. Manage. doi:10.1007/s002679900117.

Wilber, D.H., and Clarke, D.G. 2001. Biological Effects of Suspended Sediments: A Review of Suspended Sediment Impacts on Fish and Shellfish with Relation to Dredging Activities in Estuaries. North Am. J. Fish. Manag. **21**(4): 855–875. doi:10.1577/1548-8675(2001)021<0855:beossa>2.0.co;2.

Wright, D.G., and Hopky, G.E. 1998. Guidelines for the use of explosives in or near Canadian fisheries waters. Can. Tech. Rep. Fish. Aquat. Sci. 2107.

Wynn, T.M., Mostaghimi, S., and Alphin, E.F. 2004. The effects of vegetation on stream bank erosion. *In* ASAE Annual International Meeting 2004. doi:10.13031/2013.16423.

Xenopoulos, M.A., and Lodge, D.M. 2006. Going with the flow: Using species-discharge relationships to forecast losses in fish biodiversity. Ecology. doi:10.1890/0012-9658(2006)87[1907:GWTFUS]2.0.CO;2.

Zhan, A., Zhang, L., Xia, Z., Ni, P., Xiong, W., Chen, Y., Douglas Haffner, G., and MacIsaac, H.J. 2015. Water diversions facilitate spread of non-native species. doi:10.1007/s10530-015-0940-1.

Zorn, S.A., Margenau, T.L., Diana, J.S., and Edwards, C.J. 1998. The Influence of Spawning Habitat on Natural Reproduction of Muskellunge in Wisconsin. Trans. Am. Fish. Soc. doi:10.1577/1548-8659(1998)127<0995:tiosho>2.0.co;2.

APPENDIX

Table 1A: A list of the 20 previous Pathways of Effects diagrams that have been consolidated in to four.

Land-Based Activities	In-Water Activities
• *Cleaning or maintenance of bridges or other structures*	• *Addition or removal of aquatic vegetation*
• *Excavation*	• *Change in timing, duration and frequency of flow*
• *Grading*	• *Dredging*
• *Riparian planting*	• *Fish passage issues*
• *Streamside livestock grazing*	• *Marine seismic surveys*
• *Use of explosives*	• *Organic debris management*
• *Use of industrial equipment*	• *Placement of material or structures in water*
• *Vegetation clearing*	• *Structure removal*
-	• *Use of explosives*
-	• *Use of industrial equipment*
-	• *Wastewater management*
-	• *Water extraction*