A systematic review on the effectiveness of salmonid spawning habitat improvements, and recommendations to potentially increase productivity of depressed Newfoundland Atlantic salmon (*Salmo salar*) populations

A report submitted to

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INTRODUCTION

Salmon are in peril. In recent decades there have been dramatic declines in anadromous salmonids over broad geographic areas. This includes the “salmons” from the northeast and northwest Atlantic (genus *Salmo*), and the northeast and northwest Pacific (genus *Oncorhynchus*). Management of these highly migratory fishes is particularly difficult due to their complicated life history, including the use of both freshwater and marine habitats. Problems at sea are usually very different than problems in rivers, as are practical solutions. However, lessons learned in one species or geographic area often applicable to others.

Anadromous salmonid population productivity is typically constrained during the freshwater, not marine, phase of the life cycle (Behnke 2002). This limits potential population size and resiliency. The freshwater constraint can take two forms. Population productivity is usually constrained by 1) food resources, but the magnitude of the effect varies across species. It is less important in species that have short freshwater residency, like pink (*O. gorbuscha*) and chum salmon (*O. keta*), which not by coincidence are the species of greatest abundance. It has a great effect on those with a long freshwater phase, such as Atlantic salmon (*S. salar*) and steelhead (*O. mykiss*). Anadromous forms of these species are the lowest abundances of all species of salmon. Given the food constraint is density dependent, within a watershed it is very relevant at high population sizes, but of less importance if populations have crashed for other reasons. Management strategies should reflect this, but rarely do.

Populations can also be constrained by 2) space, independent of food. Salmonids spawn in gravel, usually by digging a nest (redd). Incubating embryos are killed by low oxygen, disease, predators, and also by movement (Utz et al. 2013) because they are sensitive to vibration. Incubation habitats can be naturally poor, or have become degraded due to human activities. Population productivity can be limited by a) low quality of spawning habitats. This often occurs when gravels get infiltrated by fine sediments after spawning, and embryos subsequently suffocate. Another problem is when redds are in specific conditions that are likely to wash away ("scour") at flood events. Productivity is also influenced by b) low quantity of suitable spawning habitats. This happens if the overall habitat has very limited gravels, or in average habitats if the population density is high, the amount per spawner is low (McNeil 1964). If gravel quantity is limited, salmon will use suboptimal areas for spawning (Barlaup et al. 2008), where incubating embryo survival is poor. Additionally, late spawning fish use the same areas and destroy redds made by those spawning earlier (McNeil 1964). Such superimposition creates poor stock-recruitment relationships. Like food and growth rates, quantity and quality of spawning habitats are therefore key drivers of salmon productivity.

There is a long history of attempts to improve salmonid productivity (Keeley et al. 1996, Loughlin and Clarke 2014), much of which is related to habitat alteration. This usually involves restoration of degraded habitats, but could be improvements to natural conditions. Habitat restoration sometimes works, but often fails (Stewart et al. 2009, Cooke et al. 2018). These activities are usually conducted with the best intentions, but are often not founded on the best available information (Cooke et al. 2018). There are no clear recommendations in the literature, although steps towards this have been occurring in recent years (e.g., Kondolf 2000). Actions should be based on best available information, which includes experiences across broad geographical ranges, contexts, and species, but also incorporates nuances of specific circumstances. Conducted in the right way, habitat alteration has potential to improve productivity, which can have positive impacts on population persistence, ecosystem ecology, human cultures and economies.

This report first reviews global techniques used to improve salmonid habitats, and then makes recommendations for potential habitat improvements for Atlantic salmon in Newfoundland. The review focuses specifically on methods used in attempts to improve salmonid embryo survival during the incubation stage in spawning gravels. If populations are below carrying capacity, improved embryo survival is assumed to lead to increased smolt production and thus increased spawners in the next generation than otherwise would have occurred. Through time, population size would be expected to either increase, or decrease at a slower rate than would have occurred without intervention. Increasing egg hatching success from 10-20% is functionally the same (twice as many eggs hatch) as increasing marine smolt survival from 4-8% (twice as many eggs deposited). The review excludes other habitat alterations, such as improvements to juvenile rearing or fish passage. These either increase quantity or quality of feeding habitats, which are generally not a bottleneck in productivity for depressed populations (open habitat via improvements to fish passage can make new spawning areas accessible). The review follows the general framework of that proposed by Taylor et al. (2017), but is more focused, being specific to the salmonids (Teleostei: Salmonidae, subfamily Salmoninae). It also excludes work on lake spawning salmonids, as in my preliminary assessments the issues with particular techniques were different than for river spawners. The review was conducted in a systematic way and thus should be repeatable. The goal was to identify key elements of success and failure under different contexts, in order to provide the best management recommendations.

The objectives of this report were to:

- Summarize techniques used to improve riverine salmonid spawning habitats globally
- Summarize outcomes of different techniques and identify any keys to success or failure
- Summarize specific spawning habitat requirements for Atlantic salmon, as per how it relates to possible spawning habitat intervention
- Summarize Atlantic salmon habitat interventions that have occurred in Newfoundland
- Identify if certain types of Newfoundland Atlantic salmon watersheds or populations would appear to benefit most from spawning habitat intervention

METHODS

Systematic review of primarily literature for all salmonids

A preliminary set of sources was screened to identify search terms for the systematic review. These preliminary sources were obtained from primary and grey literature using search phrases such as “Atlantic salmon spawning habitat”, “spawning habitat enhancement”, and “spawning gravel supplementation”. Key words within those sources were used to help find other articles. Over 100 preliminary articles were examined and used to identify search terms for the review (Table 1). Sources for the systematic review were acquired on February 22, 2018 using the Web of Science and Table 1. The search engine located 655 articles based on these parameters, and ranked them by relevance. I further examined the 250 most relevant.

Criteria for article inclusion were: 1) salmonid riverine spawning habitat intervention (lake spawning was excluded), and 2) the article must have quantified some measure of reproductive performance (something that is usually lacking in reports (Zeug et al. 2014)). Modeling studies were not used, nor were studies on physical aspects of gravel characteristics that did not evaluate fish reproduction. Such studies may appear in the text of this report, but are not summarized in the results of the review. Examinations of abstracts from the 250 sources identified 67 with potential to meet selection criteria. Of these 67, four sources could not be obtained in full at the time of writing. Re-examination of the abstracts indicated 3/4 probably did not meet criteria. 18 (+ 1 not obtained) of these 67, and thus the top 250 of 655 hits of Table 1 parameters, meet selection criteria and are summarized in the results. Meta-data associated with each of these 18 sources were retained and are reported.

Table 1: Search string for the identification of primary literature using Web of Science[1]. Resulted in 655 hits on February 22, 2018 (1 a duplicate). I screened the abstracts of the most relevant (as determined by WoS) 250, and deemed 67 warranted reading. Of those, only 16 directly tested reproductive performance of riverine spawning substrate enhancement.

	Search string
Taxa terms	salmo* OR trout* OR char OR chars OR charr* OR oncorhynchus OR salvelinus
	AND
Intervention terms	artificial* OR augment* OR compensat* OR enhance* OR enrich* OR improv* OR modif* OR restor*
	AND
Habitat terms	cobble* OR gravel* OR pebble* OR sediment* OR substrate* OR "spawning habitat"
	AND
Reproduction terms	alevin* OR egg* OR embryo* OR hatch* OR nest* OR redd* OR reprod* OR spawn*

[1]Web of Science is not case sensitive (Salmonid and salmonid return the same result). It does allow the use of a wildcard placemark using an asterisk (*). Salmo* takes the place of salmoniform, Salmoniformes, Salmonidae, Salmoninae, salmonid, salmonids, salmon, salmons.

Atlantic salmon spawning requirements

A second literature search identified specific spawning habitat requirements for Atlantic salmon. This information was gleaned from primary and grey literature, and was conducted outside of the systematic review (above) of spawning habitat alteration techniques for all riverine salmonids. Listed information prioritized parameters that would be most relevant for spawning habitat interventions.

Atlantic salmon habitat alterations on the island of Newfoundland

Habitat alteration effectiveness (whether spawning habitat or otherwise) for Newfoundland Atlantic salmon were summarized, as sourced from Clarke and Scruton (2002).

RESULTS

Results of systematic review of primary literature

My interpretation of the types of salmonid spawning habitat interventions is summarized in Figure 1. These range greatly in the effort required per unit area modified. Such activities fall under different definitions amongst varying literature. A passive approach (Hauer et al. 2011) includes dumping gravel along the edge of a river (e.g., McManamay et al. 2010), referred to as gravel augmentation (Brown and Pasternack 2009, Riebe et al. 2014). More active techniques (Hauer et al. 2011) are spawning bed enhancements (physically constructing riffles or cleaning gravels) and hydraulic structure placement (putting logs or boulders in riffles to try and entrain gravels to specific areas) (Brown and Pasternack 2009). Intervention levels 2-4 (Figure 1) fall within the terms gravel injection, gravel placement, and structural placement (Zeug et al. 2014). For this report (Figure 1) I refer to them as Gravel Cleaning (level 1), Gravel Augmentation (level 2), Weir Construction (level 3), Spawning Bed Creation (level 4), and Spawning Channel Creation (level 5). There is some categorical overlap with Reiser (2008).

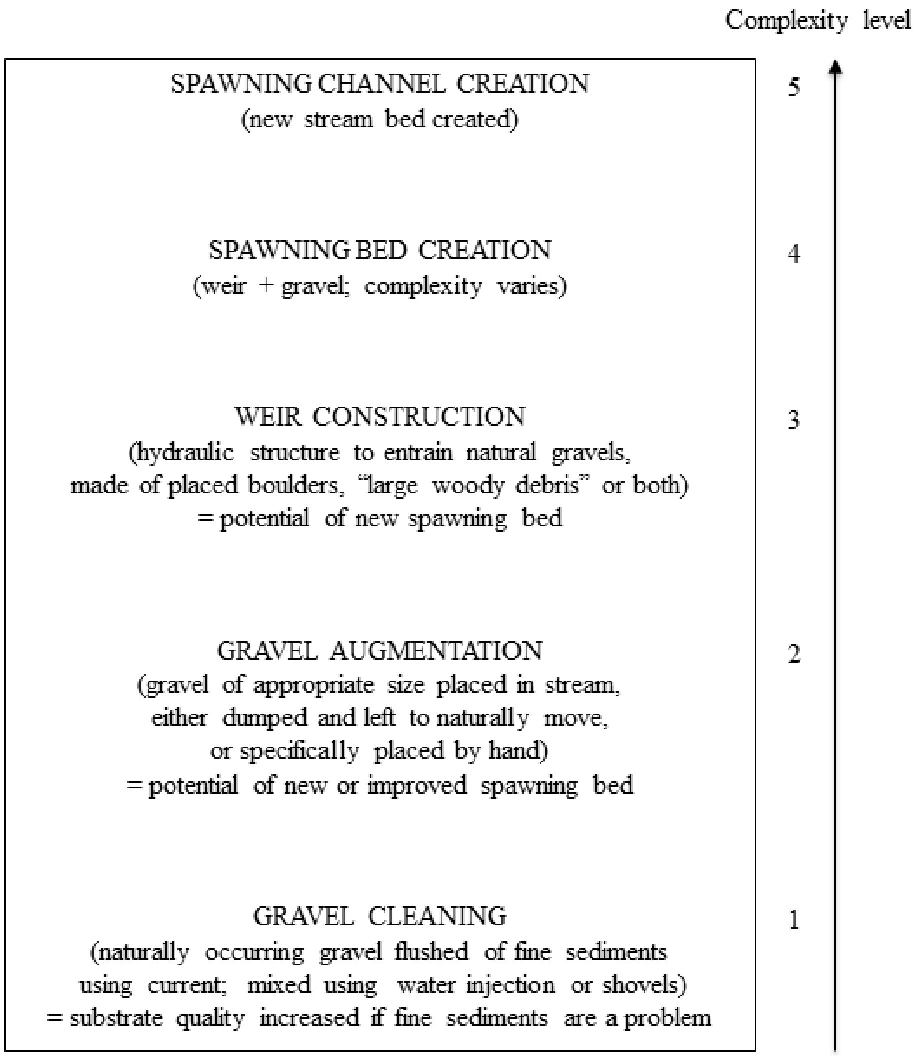

Figure 1: Types of riverine salmonid spawning habitat interventions. Complexity increases on the vertical scale. For the same area of habitat alteration, effort (and often cost) is dependent on complexity. Effectiveness is context dependent and thus pros/cons of different approaches varies.

There are numerous examples in the grey literature of when these techniques have been used. However, in very few cases has there been scientific examination of their effectiveness. When spawning habitat intervention effectiveness has been evaluated there may be a bias in whether positive or negative results appear in the primarily literature. Undoubtedly there are studies that should have been incorporated that were not picked by the search parameters used. From the systematic review only 18 published studies (Table 2) could be used to evaluate trends. Fortunately, these did encompass the variety of techniques identified in Figure 1. Most studies were from the Pacific coast of North America (largely from California, and one watershed in particular). All but potentially one study (which was written in Japanese (Nakamura 1999)) were conducted under the context of degraded habitat restoration (usually in the context of dams), not improvements to naturally poor habitats (Table 2). Fourteen of the 16 studies found positive results on salmonid reproduction (across seven species), at least in the short term. In cases of gravel augmentation, armouring downstream of a dam was the usual motivation. There was no measurable effect of intervention in one study (Zeh and Donni 1994), because fish did not spawn in gravels that had been added downstream of a dam, where infiltration of fine sediments was a problem. The one study that published a negative result is a unique situation. Spawning gravel was added for chinook salmon, but coho also used it for spawning in the fall. In spring, juvenile chinook (*O. tshawytscha*) leave the system, but young coho (*O. kisutch*) remain. However, in this dammed system agricultural water withdrawals in the summer meant these young coho became trapped (Jeffres and Moyle 2012).

Table 2: Results of systematic search from Table 1. Interventions have been categorized as in Figure 1. Other examples are available in Reiser (2008, Table 1).

Species[1]	Involve dam?	Restore or enhance	Intervention	Outcome	Comparison[2]	Result	Reference
Atlantics	dam	restore	5 - spawning channel	fish occupied	BA	+	(Loughlin et al. 2017)
brookies	dam	restore	5 - spawning channel	YOY[3] density	BA, CI	+	(Scruton et al. 2005)
browns, rainbows	dam	restore	5 - spawning channel	# redds	CI	+	(Obruca and Hauer 2016)
browns	dam	restore	5 - spawning channel	# redds	BA, CI	+	(Reiser 2008)
browns	no	unclear	4 - spawning bed	embryo survival	CI	+	(Rubin et al. 2004)
browns, rainbows	no	restore	4 - spawning bed	embryo survival	BA, CI	+	(Palm et al. 2007)
Japanese	unclear	unclear	4 - spawning bed	embryo survival	CI	+	(Nakamura 1999)
Atlantics	dam	restore	3 – weir (logs)	# redds	BA, C	+	(MacInnis et al. 2008)
coho, rainbows	unclear	restore	3 - weir (boulders)	# redds	CI	+	(Roni et al. 2008)
Atlantics, browns	dam	restore	2 - gravel augmentation	# redds	BA	+	(Barlaup et al. 2008)
browns, rainbows	dam	restore	2 - gravel augmentation	# redds	BA	0	(Zeh and Donni 1994)
chinook	dam	restore	2 - gravel augmentation	# redds	BA	+	(Elkins et al. 2007)
chinook	dam	restore	2 - gravel augmentation	# redds	BA	+	(Merz and Setka 2004)
chinook, rainbows	dam	restore	2 - gravel augmentation	# redds	BA	+	(Zeug et al. 2014)
chinook, rainbows	dam	restore	2 - gravel augmentation	embryo survival	CI	+	(Merz et al. 2004)
coho	dam	restore	2 - gravel augmentation	juvenile survival	BA	-	(Jeffres and Moyle 2012)
browns	unclear	enhance	1 – gravel breakup & wash	redd size	BA,CI	+	(Lapesa et al. 2016)
browns	dam	restore	1 - instream gravel wash	embryo survival	BA	+	(Sternecker et al. 2013)

[1] Atlantics (Atlantic salmon, *Salmo salar*), browns (brown trout, *Salmo trutta*), brookies (brook charr, *Salvelinus fontinalis*), Japanese (Japanese charr, *Salvelinus leucomaenis*), chinook (chinook salmon, *Oncorhynchus tshawytscha*), coho (coho salmon, *Oncorhynchus kisutch*), rainbows (rainbow trout, *Oncorhynchus mykiss*)
[2] before/after (BA), control/intervention (CI)
[3] young-of-year

Atlantic salmon specific spawning habitat requirements

Atlantic salmon typically spawn in the tail of pools, where water velocity increases before a riffle. Other spawning locations include the inlets or outlets of lakes (Jonsson and Jonsson 2011). In general salmon can spawn in gravel up to a size of a median diameter that is 10% of the fish's length (Kondolf and Wolman 1993). Larger fish can exert more force on gravels, and can hold in stronger currents, which move dislodged material of greater size (Kondolf and Wolman 1993). Spawning anadromous Atlantic salmon vary greatly in size depending on how long they have been at sea. Unlike in most other areas, in Newfoundland the vast majority are grilse that have spent 1 sea-winter (O'Connell et al. 2006). A summary of spawning substrate habitats for Atlantic salmon is presented in Table 3, along with intervention values deemed desirable for the small size of Newfoundland salmon. Of note, if average size of spawning salmon decreases through time, it would result in less suitable spawning habitat (Zeug et al. 2014) across generations even without changes to habitat.

Table 3: Summary of spawning substrate requirements for Atlantic salmon. Newfoundland Atlantic salmon are predominately grilse spawners (one sea-winter), with few large fish. The average spawner (52.5cm, Purchase unpublished) is much smaller than in other geographic areas, and thus would not have the same spawning requirements as other regions with multi-sea winter fish.

Parameter	Atlantic salmon requirements	Recommendation from this report for Newfoundland
Gravel size *Bigger for larger fish*	5 – 128mm (Jonsson and Jonsson 2011) 32 - 64mm (Barlaup et al. 2008) ~ 20 - 35mm for Newfoundland salmon (Kondolf and Wolman 1993)	Use 25 – 38mm (quarry 1.0 – 1.5 inches) gravel. Smaller material likely to scour too easily, but bigger material likely too difficult for grilse to move.
Egg burial depth *Deeper for larger fish*	15 – 25cm (Jonsson and Jonsson 2011) 15 - 30cm top-bottom of egg pocket (DeVries 1997) 12cm to top of egg pocket (Barlaup et al. 2008)	30-40cm of added gravel. If it is too deep, the gravel bed becomes unstable (DeVries 1997), and movement is a problem (Utz et al. 2013) Use 30cm for small Newfoundland salmon
River gradient	<3% (Jonsson and Jonsson 2011)	Very fine resolution, can measure at exact site
Water velocity *Faster for larger fish*	35 – 80cm/s (Jonsson and Jonsson 2011) 20 – 80cm/s (Barlaup et al. 2008)	Due to small size of fish, areas of 20-40cm/s, after gravel addition
Water depth	17 – 76cm (Jonsson and Jonsson 2011) 51 – 100cm (Barlaup et al. 2008)	>45cm, is correlated with other factors

Restoration/enhancement activities in Newfoundland

Scientists at Fisheries and Oceans Canada have conducted and evaluated the performance of several salmon restoration activities in Newfoundland. These were summarized by Clarke and Scruton (2002) and are presented in Table 4. Only one study is relevant to recommendations from this report. In Northeast Placentia River, spawning gravels were deemed limiting, potentially as a result of road construction (Nicks 1994, Scruton et al. 1997). Gravel from a marine beach was washed and sorted before being added to test sites (exactly how it was added is not indicated). Redd surveys and fry densities were followed for a number of years, with "very encouraging results" (Scruton et al. 1997).

Table 4: Salmon restoration/enhancement activities in Newfoundland with follow up on effectiveness. All material sourced from Clarke and Scruton (2002).

Where	What	Directly evaluated reproduction and substrate?	Intervention (Figure 1, this report)
Noel Paul's Brook	Instream structures	No	
Joe Farrell's Brook	Instream structures	No	
Cole's Pond	Nutrient addition	No	
Great Gull Brook	Barrier removal	No	
Seal Cove River	Spawning channel	Yes	5
Pamehac Brook	Spawning channel	Yes	5
Rose Blanch Brook	Spawning channel	Yes	5
Northeast Placentia River	Gravel addition[1,2]	Yes	2

[1] Used sorted gravel from a marine beach.
[2] Results were "very encouraging" but monitoring was discontinued (Scruton et al. 1997).

SYNTHESIS-REFLECTION

General patterns across species and geographic areas of intervention effectiveness

Almost all studies of spawning habitat intervention success have been conducted on restoration of gravel after the construction of dams, not enhancement in natural systems. The one possible exception that I found is written in Japanese (Nakamura 1999) and cannot be fully examined. The systematic search would have not found such enhancement efforts if either spawning habitat intervention is not being done in natural systems, or it is not being evaluated for performance. It is possible this highlights a missed opportunity for struggling populations. I think many issues are transferable across human degraded to naturally poor habitats, but it does limit confidence in interpretation of the potential to improve population productivity.

Ironically much of the literature on salmonid spawning habitats is related to sediments that are too fine (siltation), but most work on interventions via adding substrate is related to sediments that are too coarse. Poor spawning gravel can happen because of two reasons. 1) It is too fine; although salmon do not normally spawn in fine sediment, coarser material infills with silt and other fine sediment, leading to low oxygen exchange (particularly during late stages of embryogenesis). This results in poor hatching success, and is common when human activities alter catchment characteristics (road construction, clear cutting). 2) At the other extreme, substrate can be too big. Salmon have nowhere to spawn in a given river reach if substrates are too large to move. At the upper limit of suitability, fish may dig into suboptimal sized substrate, but this often results in shallow redds. These are more likely than average or deep redds to be washed away during floods. Most of the available literature on spawning habitat interventions is related to increases in mean substrate size after the construction of dams. I found no literature of the conceptual problem that certain populations maybe acutely constrained because of natural lack in small enough substrates. It is well regarded that salmonids cannot reproduce in naturally fine sedimented rivers, but sometimes migrate through these (e.g., lowland agricultural zones) to reach spawning tributaries at elevation with higher relief and coarser gravels. The problem of naturally too large of substrate seems to have been overlooked.

Studies do not exist that are long enough to measure population productivity across generations, before and after habitat intervention. Spawning habitat supplementation is usually considered successful (Brown and Pasternack 2009) if the number of redds increase (exactly at the intervened sites). During that spawning season, these spawners are from the same river, so there is not an increase in spawning for the entire population (the new redds were thus not made somewhere else). Within a whole population all that really matters is that the number of juveniles produced increases. However that hasn't been measured, but embryo survival has been quantified at times (Table 2) and seems to be improved in enhancement sites. An untested assumption is that this would lead to increased spawning numbers in future years. This is probably a safe assumption if populations are below carrying capacity of food availability.

The quantity and quality of spawning substrates are related to gravel source and movement within a watershed. Most literature is related to changes in spawning habitats through time, due to human alterations in flow regime (dams). When spawning gravels are added, high flow events can be taken advantage of to disperse them from dumped locations. However, floods are often cited as a reason why gravel supplementation may not have long-term benefits as it maybe dispersed too much with time (Kondolf 2000). Factors that affect gravel movement (Merz et al. 2006) need to be acknowledged in project planning, in order to maximize the potential for success.

Marginal habitats

Post-glaciation, only marine tolerant freshwater fishes colonized the island of Newfoundland. The freshwater fish community is very sparse compared to the rest of eastern North America. As a result of little competition with other species, Atlantic salmon use habitats in Newfoundland (like lake rearing) that are generally avoided in other areas (Dempson et al. 1996, Clarke and Scruton 2002). This may also lead to Newfoundland salmon utilizing naturally poor spawning habitats (Barlaup et al. 2008), which might be avoided in other regions. If spawning habitats contain particles that are too large, this would become more significant if the mean size of spawning salmon decreases through time.

The lack of competition from other species undoubtedly increases the natural level of productivity of salmon from Newfoundland watersheds. This results from current productivity being dependent on suboptimal habitat, which could be venerated by invasive species. Spawning habitat bottlenecks and poor primary productivity would make Newfoundland salmon more susceptible to introduced species that those in other areas.

KEY INSIGHTS AND RECOMMENDATIONS FOR NEWFOUNDLAND SALMON

Types of intervention

- On the invention scale (Figure 1, level 1), gravel cleaning (Semple 1987) would appear to not be of much help in most Newfoundland watersheds, as it is not infiltration post-spawning that is generally the problem, but lack of suitable substrate in the beginning. There maybe exceptions where it would be useful, such as downstream of logging activities or road construction.
- Spawning channel construction (Figure 1, level 5) is a massive amount of work and very expensive, and thus seems to be only useful in extreme situations, such as legislated habitat compensation for hydro projects. It is notable that in Newfoundland this is the technique with the most information on effectiveness. I do not think it is very efficient on a biologically relevant scale.

- In my opinion, the interventions with the most prospects are adding gravels (Figure 1, level 2), constructing weirs that hopefully catch gravels (Figure 1, level 3), or doing both (Figure 1, level 4). These techniques have promise in the right places.
    - Weirs (Figure 1, level 3) can be made from local material (boulders, logs – fir trees rot fairly quickly). Weirs cannot be put in large systems, so small streams are best suited. However, if there are not local gravels to get entrained (the inherent problem in many cases), they are not going to work. They would be useless just downstream of slack water (like a lake, see below), and thus locations would have to be carefully evaluated. It is important to not put them too close together or in too low of gradient (Salant et al. 2012), as in such situations they may cause more problems than good.
    - Adding gravels (Figure 1, level 2) directly gets around the lack of gravel, but one has to have access to streamside by dump truck. This would be a problem over most of the salmon habitat in Newfoundland, but specific sites could be identified. Gravel is more likely to wash away in big systems, so small streams are best suited. Small tributaries of medium sized salmon rivers would in my opinion be the most effective places for intervention. The small stream can be manipulated for spawning, but juveniles can then spread into large habitats as they get older. High flow transport can be taken advantage of to disperse gravels, but through time this also means that periodic repeat augmentation maybe necessary in future years.
- Another potential technique that could improve quality of spawning gravels is the removal of some large substrate (Riebe et al. 2014), instead of addition of small substrate. I found no example of this being evaluated in any species. The ability for salmon to dig redds is negatively affected by small boulders as they increase the mean particle size in a given unit

of area (Overstreet et al. 2016). Many of these are of a size that a person is capable of removing. In areas where gravels do occur, the spawning capacity of specific beds could be improved by the removal or rearrangement of boulders during low flow, thus decreasing mean particle size. Removing one basketball size boulder in the right area could open $1m^2$ of spawning gravel. Such a technique could be implemented on a large scale (several pools a day by a team of 2-3 people). Boulders act as weirs, so rearrangement is better than removal, as this may lead to existing gravels washing away.

Gravel used during augmentation (Figure 1, level 2)

- Gravel shape: Most cases of gravel supplementation usually use a natural source, but natural gravels are in limited supply in Newfoundland. The easiest material to acquire is crushed rock of the right size from a quarry, however it is of an un-natural shape as it has not been exposed to weathering. I saw only one comment on gravel shape (Rubin et al. 2004), which expressed concern that cut gravel could damage salmon during spawning. In my opinion this is not very important. Few Atlantic salmon survive to spawn a second year, so even if jagged edges did damage fish, it seems not to be of population concern.
- Gravel size uniformity: Supplemented gravel can be all one size, a range of a few sizes, or mixtures, including coarse sand. There was one suggestion (Franssen et al. 2014) that it is important to not make gravel too clean, as coarse sands and fine gravel (0.5-4mm) can keep really fine sediment from filtering into the new substrate. This might be less of an issue in watersheds weathering granite lithologies (Franssen et al. 2014). I am dismissing this issue as not being overly important in most cases in Newfoundland.

- Gravel size: The smaller the size of the gravel, the more it moves. A common problem is that if small gravel is added it is more likely to wash away than larger material. Thus gravel on the bigger end could be used to reduce this. Ideally gravel will stay stable during incubation, but move under some conditions after incubation (Brown and Pasternack 2009). It can be too big as well. Fish on the small size end cannot dig deep into it and thus make shallow redds (DeVries 1997), which are more likely to “scour”. Also there was one report (Palm et al. 2009) that documented increased predation on eggs by sculpin in bigger gravel. There are no freshwater sculpin in Newfoundland, and I do not think predation by trout would be substantially different in big or small gravel of relevant ranges. I do not think it is an important issue.
    - Ideal spawning gravel size is dependent on the size of spawning fish. Newfoundland salmon are predoiminatnly grilse (1 winter at sea) with a mean around 52.5cm. Max moveable gravel would thus be about 2.0 inches. My suggested gravel size would thus be 1.0-1.5 inches (Table 3). I am recommending gravel on the large end of the normal spectrum be used, as although not optimal it is more likely to achieve long term benefit than the small end (which is more likely to wash away).

Types of watersheds where gravel augmentation is most useful

- Most work has been done on the Pacific coast, with tectonically active geology, and long river systems that contain no or very few lakes. Gravel is generally not in short supply, but becomes a problem when a dam is created. Dams create slack water, which traps downstream moving sediments, and gravel accumulates in the reservoir. The streambed downstream of the dam becomes “armoured” as only the large substrate remains after existing smaller gravel washes away (Kondolf 2000). A key insight is that lakes are functionally identical to reservoirs. Any gravel coming downstream is trapped by lakes/ponds (Palm et al. 2007).

- Much of eastern North America is very different than the Pacific northwest, where most work in on spawning habitat intervention has been conducted. The underlying geology is fundamentally different, which limits gravel supply. River gradients are lower which act (like reservoirs and lakes) as sediment sinks, limiting movement of gravel (Wilkins and Snyder 2011). Newfoundland in particular has lots of lakes/ponds. The combination of geology, glacial history, low gradient streams and abundance of lakes in Newfoundland, combine to produce lack of spawning gravel. It would be predicted to be worse the closer to a lake outlet a given location is.
- I think two key papers can be used to identify specific areas for potential spawning habitat intervention in Newfoundland watersheds.
    - Based on Wilkins and Snyder (2011), from topo maps or GIS, river gradients can be used to identify whole watersheds or parts of watersheds that are likely to lack gravels. This can be done on a large scale to identify candidate watersheds, or to identify river reaches on smaller geographic scales.

      o River reaches suspected of poor amounts of spawning gravels by the above method (Wilkins and Snyder 2011) could then be examined to quantify amounts of spawning habitat using a new predictive tool published by Overstreet et al. (2016). This method requires size of spawning fish (which is known), and substrate size (which can be attained via established pebble count procedures (Kondolf 1997)). It could be combined with a simple survey of general habitats (Scruton et al. 1992). Outputs from the model (Overstreet et al. 2016) are either:

        - Fraction of the stream bed that can be used by salmon
        - Number of redds that can be built in a useable area
        - Number of eggs that can be incubated in given areas (e.g, 100m^2 units)
    - I recommend a research project that combines the above techniques (Wilkins and Snyder 2011, Overstreet et al. 2016) to identify specific areas for possible enhancement. Watersheds with impassable barriers to salmon could be excluded, and can be identified from Porter et al. (1974). Predictions from this activity would need to be combined with knowledge of road access in order to further narrow down areas for enhancement. Depending on the geographic scale, very useful results could be acheived using the equivalent scope of 1 MSc project.

POTENTIAL RISKS

There seem to be two obvious biological risks to salmon from the recommended interventions. 1) Salmon may spawn under natural conditions and have low hatching success due to low gravel quantity or quality. Spawning gravel beds could be created and used by fish. Based on work elsewhere, this should improve mean hatch success, but if these beds are very unstable, then scour during incubation maybe more pronounced than under natural conditions, and embryo survival could be reduced. Given Newfoundland salmon are small, they do not dig deep redds, and shallow redds are more likely to scour (Montgomery et al. 1996). If such a problem exists, it would likely diminish substantially across years, as gravels stabilize. Two ways of mitigating this potential threat would be to place gravels in streams long before the spawning season (but after alevin emergence in May) to allow time for stabilization after high flow events, and to not create gravel beds that are too thick (eggs will be deposited in the top 30cm no matter how thick the bed is). 2) It may be possible the enhanced gravel beds would preferentially benefit species other than salmon, and thus may increase their densities and interactions with salmon. The most obvious candidate for this problem would be brown trout (*S. trutta*), which at present are not know to occur west of the Burin and Bonavista Peninsulas. Brown trout typically spawn earlier than salmon and thus superimposition would not be a problem.

FINAL THOUGHTS ON SCOPE FOR IMPROVEMENT

I believe the combination of geology, glacial history and abundance of lakes limits salmon spawning gravels in Newfoundland. I think this is less of a problem on the west coast of the island, with higher relief and fewer lakes, but it maybe acute in other areas. In some depressed populations that are well below carrying capacity of food, this maybe a key bottleneck in potential recovery. Although research on improving spawning gravels in other areas has been focused on restoring degraded habitats, I believe there is good potential to improve salmon productivity via intervention to naturally poor spawning habitats, something that fits a recent call to enhance productivity (NASCO 2010). One does not have to re-invent the wheel, lessons learned in other areas are applicable (Kondolf 2000). Buried in a lengthy report is one paragraph where Buchanan et al. (1989) dismissed this idea in Newfoundland, whereas in the one situation where it was tried and monitored the results were very encouraging (Scruton et al. 1997).

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