Assessment of measures to assess compensation and mitigation as related to the creation, rehabilitation, or restoration of spawning habitat for fluvial or lacustrine spawning salmonines

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Foreword

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

Research documents are produced in the official language in which they are provided to the Secretariat.

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ABSTRACT

Salmonine spawning habitat is often the focus of fish habitat restoration efforts. To guide these efforts, I review the importance of spawning habitat, measures to mitigate development related habitat destruction and degradation, methods of constructing new habitat and how to monitor constructed spawning habitat productivity. The assessment considered peer reviewed literature and agency files for both fluvial and lacustrine spawning salmonines. Although agency files involving creation of spawning habitat were limited, there was ample evidence in the peer reviewed literature suggesting that spawning habitat for both fluvial or lacustrine spawners can be created that supports natural reproduction and can contribute to successful recruitment to the adult populations. Multiple methods exist for directly or indirectly assessing the use, relative success, and quality of compensatory habitat. The challenge for practitioners is in the assessment and understanding of the effects of specific spawning habitat creation on populations, whose members may be temporally (e.g., spawning run may be several years removed from spawning habitat creation) and spatially (e.g., upstream spawning habitat supporting a downstream population) removed from habitat creation activities. Consequently challenges exist for developing sampling designs that make it possible to relate local spawning habitat creation projects to entire populations, and resolving the links between habitat creation and population response.

Évaluation des mesures de compensation et d'atténuation liées à la création, la réhabilitation ou la restauration d'habitat de frai pour les salmoninés qui frayent dans les cours d'eau ou des lacs

RÉSUMÉ

L'habitat de frai des salmonidés fait souvent l'objet d'efforts de restauration de l'habitat du poisson. Pour guider ces efforts, j'examine l'importance de l'habitat de frai, des mesures pour atténuer la dégradation et la destruction de l'habitat liées au développement humain, des méthodes de création de nouveaux habitats et des méthodes de suivi de la productivité de ces nouveaux habitats de frai. Pour cette évaluation, on a pris en compte la littérature scientifique évaluée par les pairs et les dossiers de différentes agences sur les salmoninés qui frayent dans les cours d'eau ou des lacs. Même si les dossiers des agences contenaient peu d'information sur la création d'habitats de frai, d'après la littérature scientifique consultée, de nombreuses preuves suggèrent qu'il est possible de créer des habitats de frai pour les reproducteurs qui frayent dans les cours d'eau ou des lacs. Ces habitats soutiennent la reproduction naturelle et peuvent contribuer au recrutement des populations adultes. Il existe de nombreuses méthodes pour déterminer, de manière directe ou indirecte, l'utilisation, la réussite relative et la qualité de l'habitat compensatoire. Le défi pour les praticiens se pose au niveau de l'évaluation et de la compréhension des effets de la création d'habitats de frai sur les populations, lesquelles peuvent se trouver éloignées des activités de création d'habitats dans le temps (p. ex., entre la création d'habitats de frai et la montaison plusieurs années peuvent s'écouler) et l'espace (p. ex., un habitat de frai en amont qui soutient une population située à l'aval). Par conséquent, le défi est de mettre au point une méthode d'échantillonnage qui permette de rapprocher les projets locaux de création d'habitats de frai et des populations entières ainsi que de comprendre les rapports entre la création d'habitats et la réponse des populations.

INTRODUCTION

Habitat loss and degradation caused by extraction of natural resources, industrial processing, agriculture, channelization, and urbanization threaten the sustainability of fisheries resources. In Canada, the principal legislation for the management of fisheries and fish habitat is the Fisheries Act. Under the Act, management strategies focus on preventing the harmful alteration, disruption, or destruction (HADD) of fish habitat. To guide implementation of the Act, the Department of Fisheries and Oceans (DFO) developed a "Policy for the Management of Fish Habitat" (hereafter, the Policy (DFO 1986)). The guiding principle of the Policy is to ensure "no net loss of productive capacity of fish habitats" (NNL; Minns et al. 1996). Productive capacity is defined in the Policy as "the maximum natural capacity of habitats to produce healthy fish… or to support or produce organisms upon which fish depend" (DFO 1986, p. 28). When developments that will alter fish habitat are proposed and compensation programs are required, the surrounding policy assumes the ability to quantify effects of a HADD on fish production and that determining NNL can be achieved. This in turn, presumes that the habitat needs of species are known, that the relationship between habitat and fish production is known or can be determined, and that there is a reference area free from disturbance that can be used to provide a measure of the effectiveness of compensation measures taken to ensure NNL (Minns 1997). Frequently, however, one or more of these assumptions are not met. For a number of reasons, most assessments of habitat compensation must rely on indirect measures of effectiveness (Minns 1997).

Despite the critical importance of NNL to fisheries management in Canada, few studies have evaluated the effectiveness of mitigation or compensation measures within this framework. Minns et al. (1996) questioned the scientific rigor of habitat compensation programs and suggested that many are rushed with relatively little known about actual outcomes. Harper and Quigley (2005) reported, based on a national review of Fisheries Act compliance, compensation projects were found to be inadequately documented in almost all projects. A determination of NNL based on a review of files could only be made in 14% of the projects reviewed. Quigley and Harper (2006a) reported that biological compliance with NNL was met in only 58% of compensation projects. This lead Quigley and Harper (2006b) to suggest that at best, fish habitat compensation methods were just slowing the loss of fish habitat. The Harper and Quigley (2005) review uncovered a surprising naiveté of the effectiveness of compensation measures in that median compensation ratios (1.13:1) were only slightly greater than 1 when there was considerable uncertainty as to the effectiveness of the compensation measures undertaken. In 25% of the cases compensation ratios were less than 1, and the ratios used were not dependent on how critical habitats were. It appears also that there is little time committed to assessing the effectiveness of this compensation. Drodge et al (1999) reported that habitat management devoted only 1.7% of their workload to compensation monitoring based on a national study.

An inability to make a NNL determination has been related to the selection of performance criteria that are qualitative but not quantitative. As a result, the criteria used do not provide an indication of the effectiveness of the compensatory measure in achieving NNL according to Harper and Quigley (2005). These authors also found evidence of the failure of pre-impact monitoring to establish a proper baseline, and a failure of monitoring programs to establish the effectiveness of compensatory habitats. Their review highlighted the need for a standardized approach to designing and implementing monitoring programs that can assess the effectiveness of habitat compensation in achieving NNL.

The creation of spawning habitat unlike the creation of other fish habitat types used by fish has fairly clear implications for fish recruitment (Palm et al. 2007; Merz et al. 2004) and ultimately

fish production (Roni et al. 2008). Benefits may arise from a combination of reduced competition for limited food resources at the newly hatched or alevin stage of salmonines that have a limited home range having limited food resources (Floyd et al. 2008; McDonald et al. 1992), or increased egg survival through the reduction of competition for spawning sites reducing the occurrence of redd superimposition (Hayes 1987). In addition new spawning gravels would seemingly be easier to excavate than natural gravels thereby reducing energetic costs and mortality associated with digging (Richards and Pickering 1978, Ferguson and Rice 1980). New spawning gravel at least initially, would have less fine sediment which can result in reduced embryo survival (Hausel and Coble 1976, Chapman 1988).

In part because of the reduced mobility of early life stages such as sac-fry and alevins, and relative ease in observing spawning and the development of early life stages *in situ*, creation of spawning habitat probably has the greatest knowledge base of all types of compensation habitats constructed (Armstong et al. 2003, Gibson 1993, Marsden et al. 1995). The relatively greater understanding of spawning habitat and habitat requirements stems in part from spawning habitat being perceived as critically important. The importance of spawning habitat is believed to depend largely on substrate suitability and oxygen requirements and less so biological attributes until the end of the embryonic period. As spawning habitat is often perceived to be of critical importance to fish populations (Rosenfeld and Hatfield 2006) it is rarely destroyed during construction activities in water. Negating any need for compensatory habitat but is often created to replace the productivity lost following the destruction of other types of habitat. Rarely though is there any assessment of whether spawning habitat is in fact limited or whether it contributed to increased recruitment (Minns et al. 1996).

To compensate for the destruction of a nearby lake, a spawning reef was constructed in Snap Lake in NT to serve as spawning habitat for Lake Trout (*Salvelius namaycush*) and Round Whitefish (*Prosopium cylindraceum*) and provide habitat for small fish and invertebrates (Fitzsimons unpubl. data). However, neither was there any knowledge of whether spawning habitat was limiting in Snap Lake or whether the new reef contributed to increased recruitment. Apart from uncertainty about the need, in this case equating production provided by the compensatory reef spawning habitat with the destruction of an entire lake is impossible because existing metrics of productivity cannot account for the difference in the destroyed and created habitats.

Despite the availability of information on the appropriate physical and chemical attributes for spawning habitat and for a variety of salmonines (Gibson 1993, Armstrong et al. 2003, Crisp 1993, Louhi et al. 2008), there remains considerable uncertainty in terms of creating and replicating the functionality of natural spawning habitat in the wild. For example, the lacustrine spawner Lake Trout appears to select spawning habitat that offers a compromise between sufficient exposure to a wind fetch that creates a wave energy and current that can maintains interstices free of fine material and provide adequate water quality (Sly 1988). Excessive physical disturbance can result in either damage to eggs during early sensitive stages of development or egg dislodgement although habitat with these attributes may be selected for (Fitzsimons 1994a, b, Fitzsimons 1995, Marsden et al. 1995, Fitzsimons et al. 2007). Fitzsimons and Marsden (2014) reported the greatest spawning use by Lake Trout was for the portion of the reef having the highest potential for egg loss based on the use of artificial eggs which they used as a surrogate for levels of physical disturbance. Although the area used for spawning had a high potential for egg loss, for those eggs that remained in place, these authors could find no relationship between survival to the eyed egg stage and recovery of artificial eggs. A related problem for fluvial spawners involves the use of appropriate egg burial depths during spawning (DeVries 1997) which shows some relationship to the size of fish building them (Crisp and Carling 1989). Excessively shallow egg burial depths may result in egg washout during stream

bed scouring associated with flooding (Crisp 1989, Ottaway et al. 1981). However, burial of eggs at excessive depths may subject them to increased accumulation of infiltrated fine sediments reducing the availability of oxygen to developing embryos (Meyer et al. 2008, Hamor and Garside 1976, 1977).

Early life stages undergo a critical transition in their nutrition at the end of the yolk-sac stage when they switch from endogenous (e.g., subsisting on the yolk-sac) to exogenous (e.g., consuming invertebrate prey) nutrition (Heming and Buddington 1988). At this transition the availability of invertebrate prey of appropriate size at environmental conditions appropriate for their efficient capture may be paramount for survival, and progressive and sustained increase in size (Elliott 1989). In order to obtain sufficient food resources, early life stages may trade off short term survival for a longer period of vulnerability to predation due to slower growth. Due to reduced productivity in Arctic lakes, the effects of such decisions may have more profound effects as resource availability is reduced for both predatory fish and their potential prey where it is imperative that positive growth be maintained (McDonald et al. 1992).

The availability of food resources in lacustrine environments appears to far exceed that in fluvial environments. Floyd et al. (2008) reported that an Atlantic salmon fry density of 350/100 m^2 may approach a streams carrying capacity whereas for Lake Trout, Marsden et al. (2005) reported emergent fry densities ranging from 60-930/100 m^2 for self-sustaining stocks. Such high fry densities may represent the relatively high compensatory ability of Lake Trout and appear to be sustainable for at least part of the first year of life. Bronte et al. (1995) reported densities of YOY in July for a spawning reef in Lake Superior approaching from 100 to 700/100 m^2 depending on year. Lake Trout in Lake Superior are considered fully self-sustaining (Hansen 1999) suggesting that such high alevin densities are sustainable.

THE IMPORTANCE OF SPAWNING HABITAT FOR MAINTAINING RECRUITMENT AND POPULATION STABILITY

Availability of spawning habitat is critically important for maintaining recruitment of populations of fluvial (e.g., Brown Trout (*Salmo trutta*), Atlantic Salmon (*Salmo salar*), Pacific salmon) and lacustrine (e.g., Lake Trout, beach spawning Sockeye Salmon (*Oncorhynchus nerka*), and Kokanee Salmon (*O. nerka*)) spawning salmonines, especially at low population abundance. High early survival provided by high quality spawning habitat contributes directly to the density dependent compensatory capacity of a stock. For example, if early Lake Trout survival is reduced, the level of fishing mortality at which the compensatory capacity of the population is exceeded declines sharply (Evans et al. 1990). Fishing mortality can be extremely important regulator of a variety of fish species and easily overwhelm the compensatory capacity of fish stocks (Myers et al. 1996).

The ability of spawners to produced spawners appears conserved across species. At low population abundance the number of spawners produced per spawner each year or maximum annual reproductive rate for salmonines appears to vary little from that of other species (Myers et al. 1999). Adequate high quality spawning habitat is important for achieving or at least having the potential for achieving the maximum annual reproductive rate, and is central to the population growth rate *r* (Cole 1954, Pimm 1991, Myers et al. 1997), limits to overfishing (Mace 1994, Cook et al. 1997, Myers and Mertz 1998), estimation of the dynamic behaviour of a population (i.e. whether it has oscillatory or chaotic behaviour), extinction models, and population viability analysis (Lande et al. 1994). In addition having adequate spawning habitat is important establishment of biological reference points for management (Groves et al. 2013), and the estimation of long-term consequences of mortality caused by pollution or industrial development once sources of mortality are removed.

Recruitment which can be highly dependent on the availability of spawning habitat, can be the major source of population variability through its effects on year class strength and this has been widely documented for both marine (Caley et al. 1996) and freshwater fishes (Milner et al. 2003) For Brown Trout, a fluvial spawner, Lobon-Cervia (2009) reported that recruitment was a major determinant of year-class strength and hence of population size. Similarly Bronte et al. (2002) reported for Lake Trout, a lacustrine spawner, that year class strength was defined during age-0 while fish were still associated with the natal reef.

RESTORATION OF SPAWNING HABITAT

Restoration of habitat can be necessitated by habitat lost to the effects of inappropriate land-use practices, channelization, deforestation of the riparian zone, or the loss of woody debris (Palm et al. 2007, Fausch and Northcote 1992, Crispin et al. 1993). For fluvial spawning fish spawning habitat restoration (SHR) generally falls into three categories. These include gravel augmentation, hydraulic structure placement, and spawning bed enhancement. Because of the nature of these three types of restoration, while a particular spawning outcome can be assigned with greater certainty for some activities, what is gained in the ability to detect cause-effect linkages may be at a sacrifice to the longevity of the benefit associated with that activity. Spawning enhancement has been achieved by the direct modification of the bed to provide immediate spawning habitat (e.g., riffle construction, bed ripping, and riffle cleansing). Although such enhancements may quickly provide usable spawning habitat, a limited project lifespan may result without adequate consideration of geomorphic processes or regular gravel replenishment (Kondolf 2000). Gravel augmentation involves dumping clean spawning gravels into piles along the edges of a river (usually just downstream of a dam) and allowing natural hydrologic processes to distribute it downstream. For this approach to yield usable spawning habitat, practitioners must assume high flows occur in the near future, that augmented gravels entrain during high flows, and that gravels do not fill holes or pools but instead, deposit as bars or riffles. Hydraulic structure placement of large woody debris (LWD), boulder clusters, v-dams or similar structures can alter hydraulics in such a way that spawning gravels are deposited in the vicinity of these structures (Brookes et al. 1996, Floyd et al. 2008, MacInnis et al. 2008). This technique relies on an adequate supply of gravel from upstream and an active bedload transport regime to deliver it. Such structures may also be intended to provide refugia, cover and habitat heterogeneity (Van-Zyll-De-Jong et al. 1997). In summary, spawning habitat projects are typically reach-scale restoration activities sometimes, but not necessarily nested within a larger, long-term basin scale management plan (McBain and Trush, 1997). It is relatively straight forward relating the effects of the aforementioned actions on the activity of spawning adults but becomes increasingly difficult to relate their importance to success at subsequent life stages which are of progressively greater relevance to the success of populations (Fig. 1).

Restoration of lacustrine spawning habitat has been reported but there are far fewer examples of restoration of lacustrine spawning habitat compared to fluvial habitat. Restoration was necessitated by spawning habitat lost to the effects of water level fluctuations (Wilton 1985, Kerr 1998), changes in sediment dynamics, or excessive nutrient addition. This has been approached by augmentation or enhancement of spawning habitat at or below existing water levels, or the creation of new spawning habitat (Fitzsimons 1996). Unlike fluvial spawning habitat, it is not practical to use physical geomorphic processes to recreate spawning habitat as is possible for rivers. Most spawning habitat for lacustrine spawners like Lake Trout, is believed to be the result of glacial processes that preceded the expansion of Lake Trout populations after the last glaciation (Eshenroder et al. 1995, Power 2002). The placement of new material involves a compromise between the probability of infilling of interstices by fines and the mass movement and displacement of the material deposited during storms. Siting of material for a

spawning reef also needs to take account of the stability of the underlying sediment which may be eroded by vertical currents created by the reef itself especially in areas of high energy and result in scour and infilling of the reef structure (Sheng 2000).

MITIGATION ACTIVITIES

FLUVIAL SPAWNERS

The negative effects of fluctuations in flow on fish habitat below hydroelectric facilities are well known (Graybill et al. 1979, Ward and Stanford 1979, Stober et al. 1982, Petts 1984, Cushman 1985, Bain et al. 1988). As a result of changes in flow regimes, fluvial spawning habitat may be alternately shallower or deeper than preferred. Although shallower water depending on the depth of water can physically limit access to spawning habitat and in the case of dewatering, prevent access altogether, it appears that for some salmonines they can adjust to water being considerably deeper than preferred and still spawn successfully (Swan 1989). Regulation of flow within limits appropriate to the spawning depth used, has been effective in increasing spawning habitat wherein some species like pink and coho salmon that utilize much shallower habitat at the channel margin than Chinook salmon (*O. tshawytscha*) that use the mid channel, receive the greatest benefit (Connor and Pflug 2004).

As well as improving spawner access, flow regulation to avoid dewatering has also been shown to be effective in reducing egg and embryo mortality especially during the post hatch, pre-emergence period (Stober et al. 1982). Reduction in flow is also effective in reducing washout of redds. Seiler et al. (2001) demonstrated a strong negative relationship between peak flow and egg-to-migrant survival suggesting widespread gravel scour with high levels of egg and fry mortality. Diel reductions in flow (down ramping) can result in periodic high levels of fry stranding on gravel bars and potholes. Pflug and Mobrand (1989) found that salmon fry were most susceptible to stranding during daylight hours at all tested down ramp rates. Salmon fry stranding rates increased seven- to eight-fold when downstream ramping occurred during the day instead of at night. It's evident that by maintaining appropriate minimum flows during incubation and minimizing the total variation in flow between spawning and the time of emergence results in the greatest benefits (Connor and Pflug 2004).

LACUSTRINE SPAWNERS

In instances where water levels drop below the depth of known spawning habitat for lacustrine spawners like Lake Trout, it may be possible to block access to this habitat, prior to the spawning period, forcing fish to spawn at alternative sites. McAughey and Gunn (1995) were able to successfully divert Lake Trout spawning from historic spawning areas in a small inland lake to alternate habitat in the same lake by blocking access to the historic spawning areas using tarpaulins. The alternate habitat used for spawning had a similar range of conditions (e.g., area, substrate size, water depth) to the historic spawning areas, although some of the alternate sites had limited interstitial space. It's noteworthy that of the new sites used by Lake Trout in Whitepine Lake a small lake in central Ontario, at only 50% of the new sites were fry detected suggesting that while habitat can be detected and used for egg deposition it may not have the requisite characteristics to successfully incubate eggs. Indeed the work of McAughey and Gunn (1995) suggests that Lake Trout have an innate ability for recognition of site characteristics such as substrate size and have successfully colonized new waters (Olver and Lewis 1977, Purych 1980, Hitchins and Samis 1986), but the establishment of successful recruitment may involve a sequential hierarchical process possibly reinforced by evidence of successful natural reproduction. There are laboratory (Foster 1985) and field (Bronte et al. 2002) studies that suggest that Lake Trout imprint to specific sites possibly related to residues of bile acids

excreted by advanced developmental stages (Hara et al. 1984, Zhang et al. 2001) so highly relevant to the suitability of a particular site for successful reproduction. Such bile acids may be an important determinant of a particular site's suitability for spawning. In such a process Lake Trout may initially select spawning sites in a large area of a lake and probably on a windward shore as a type of bet hedging (MacLean et al. 1990). Selection of suitable substrate alone may provide only nominal protection of eggs from the effects of egg predators and physical disturbance. In addition egg survival on cobble is apt to vary depending on the amount of wind exposure and co-occurring sediment accumulation (Flavelle et al. 2002). The effects of egg predation and physical disturbance are liable to be experienced by embryos at relatively early developmental stages. At this time, eggs have not had an opportunity to settle into interstitial spaces (Marsden et al. 1995a), reach a developmental stage that is not sensitive to shock (Fitzsimons 1994), and while the oxygen demand of the egg is relatively high because of ambient temperatures (Garside 1959) but where oxygen availability may be reduced because of high biological oxygen demand of settling material (Sly 1988, Sly and Evans 1996).

Lake Trout spawning depth is strongly related to lake area (Fitzsimons 1994). As a result, employing methods like that used by McAughey and Gunn (1995) to cause the use of alternate spawning habitat to circumvent the effects of a post-spawning lake drawdown may be ineffective. Lake Trout may spawn at alternate spawning habitat but they may still spawn at the same depth and thus be still susceptible to the negative effects of lake level drawdown. The strong attraction shown by spawning Lake Trout for artificial substrate however may provide a means of attracting Lake Trout to alternate suitable spawning habitat located below the level of a lake drawdown and hence avoid the negative effects of drawdown on egg survival (Fitzsimons 1996; Marsden et al. 1995a, b). The creation of artificial deeper water spawning areas adjacent to and 1.4 m deeper than natural sites in a small inland lake produced a partial transfer of reproduction (Benoit and Legault 2002). It was only after the natural sites had been covered with tarpaulins though that these authors observed a complete transfer of spawning to the artificial spawning area.

The greater depth associated with spawning habitats built below adjacent natural habitat can prevent the negative effects of drawdowns on eggs, but may increase the exposure of eggs to fine material which has been associated with reduced egg survival (Sly and Evans 1996, Sly 1988). The effects of wind generated currents that tend to prevent the accumulation of fine material (Sly 1988) are progressively diminished with increasing water depth (Leonetti 1997). As a result with increasing water depth, cobble substrate can accumulate increasing amounts of fine material leading to reduced water quality and possible suffocation of eggs. This would be especially the case for artificial habitat constructed below the mud deposition boundary depth (DBD) (Rowan et al. 1992). Rowan et al (1992) provided an equation relating fetch (km) (F) and slope (%) (S) to DBD:

$$\text{Log DBD} = -0.107 + 0.742 \log F + 0.0653 S$$

Using the equation of Fitzsimons (1994) relating spawning depth (SD) to lake size (LS):

$$SD = 0.07 + \log LS$$

it may be possible to calculate the limits to which artificial spawning habitat can be constructed but still be above the DBD but this would require testing and verification in the field.

Post spawning, most issues with the use of spawning habitat by lacustrine spawners like Lake Trout and requiring compensation, relate to lake level drawdown (Wilton 1985, Kerr 1998) to below spawning depths resulting in dewatering and/or freezing of eggs. To mitigate such effects, knowledge of spawning depth can be used to limit the extent of drawdown to depths above which eggs are neither dewatered nor frozen. Spawning depth can be estimated from the

relationship between spawning depth and lake area developed by Fitzsimons (1994). Although lake area explained a high proportion of the variation in spawning depth based on the R^2, some residual variation existed. Where greater precision is required spawning depth can be measured directly as was done by Fitzsimons and Claramunt (unpubl. report[1]) who used a sigmoidal curve to model the relationship between cumulative egg deposition and depth. Using such a relationship these authors were able to estimate the effects of different water withdrawal regimes on lake levels associated with hydroelectric development on Nonacho Lake.

REVIEW OF COMPENSATION ACTIVITIES INVOLVING SPAWNING HABITAT

FLUVIAL SPAWNERS

Projects from three separate geographic areas related to compensation and involving fluvial spawners were reviewed.

Brierly Brook, NS

This work, described in MacInnis et al. (2008) and Floyd et al. (2008), evaluated the use of artificial large woody material and its influence on spawning by Atlantic Salmon in small sections of Brierly Brook. Several different endpoints were evaluated but redd counts in a 50-m segment of stream was the predominant method used. No calculations of NNL were made in this work.

MacInnis et al. (2008) described results for compensation work on a 12.7 km section of Brierly Brook using the unmodified James River as a reference. No redd counts were made in Brierly Brook in the years preceding the compensation work so Macinnis et al. (2008) were unable to employ a BACI design to evaluate their results. Instead they used a reference-impact approach to evaluate if NNL had been achieved. As the data were strongly nonnormal and contained many zero counts, it was not possible to use parametric statistics. Instead the authors used a chi-square test with expected redd counts assumed equal for the reference and impacted watercourses. The results clearly showed a statistically significant and positive effect of the compensation activities on spawning activity and these appeared to be evident over a nine year period although there was only three years of overlap between measurement on reference and impacted watercourses. It was not clear that the artificial woody structures were responsible for all of the increase in spawning activity. By differentiating the types of material redds were constructed on, a direct effect of artificial structure on spawning was only evident for 24% of the redds in Brierly Brook.

The work of Floyd et al (2008) reported on a much smaller section of Brierly Brook (1 km) but again evaluated the effect of artificial large woody material. This evaluation included an old restored area (ORA) and a newly restored area (NRA) as impacted areas, and compared then to an unmodified reference area (URA). The metrics used included measures of Atlantic Salmon fry (no./100 m^2) and 1+ parr (no./100 m^2) and redd density (redds/100 m of stream length). No statistics were provided for either the fry or parr data. A combination of ANOVA to compare redd density among areas and t-tests to compare redd density between areas, were used to assess spawning activity. A significant linear relationship between redd density in the NRA area before restoration and URA was used to establish the increase in spawning that occurred post-restoration in NRA. Fry density appeared to be higher in the NRA relative to the URA but there

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[1] Unpubl. rep. on the assessment of the effects of predicted water level fluctuations associated with the Taltson Hydroelectric Expansion Project on Lake Trout reproduction in Nonacho Lake, NT.

was no pre-restoration data for the NRA so it's not clear if this area may have been naturally more productive prior to the alteration. In addition while there was over a two-fold increase in fry density in NRA between 2003 and 2004 over this same time period, there was over a three-fold decline in fry density in ORA. The NRA appeared to have a slightly higher parr density than URA, but all the data for NRA was for post-restoration. Moreover, parr density in NRA was less than one-half that in ORA. The redd data was clearest as to the beneficial effects of the restoration activities. For the ORA, post-restoration there was a dramatic and sustained increase in redd density. Moreover, using the regression relationship between redd density in URA and NRA, it was evident that restoration resulted in a significant increase in redd density in NRA. Despite the clear indications of increased number of redds, coherence with the fry data was lacking. For 2003 when redd density was successively greater in the order URA<NRA<ORA, the fry densities that would have been the result of these redds, showed no difference among areas. The parr density patterns among the three areas were similar to the redd density patterns although Floyd et al (2008) suggested that parr density was more reflective of parr habitat than spawning success.

Rose Blanche River, NL

This work, described by Scruton et al (2005) involved compensation related to the destruction of fluvial habitat resulting from construction of a reservoir. This compensation involved construction of a spawning and rearing channel in a flood overflow channel and improved fish passage. Preconstruction data were only available for one year and post construction comparisons were made for YOY Brook Trout (*S. fontinalis*) between the compensation channel (impact) and the river main stem (reference) to infer spawning. The density of YOY Brook Trout increased in both the impact and reference habitats over the three years of post-construction monitoring but the density in the impact habitat was always significantly greater. Although these authors did not make calculations of NNL on YOY Brook Trout, for total fish biomass that included all stages, these authors reported that NNL was approached in the second year post construction and by the third year a net gain was achieved.

Yukon River, YT

This work, that has yet to be formally reported on, involved the construction of three spawning channels (Figs. 2-4) on the Yukon River in the vicinity of Whitehorse to compensate for habitat lost as a result of road construction. There appeared to be no formal objective approach for monitoring the success of this compensation work other than the presence of Chinook Salmon redds. It's evident in this regard that the monitoring program suffered from a lack of both temporal (before-after) and spatial (reference-impact) rigor. Although some redds were apparently constructed which were associated with the spawning channels the lack of documentation makes it impossible to determine at what level the channels functioned if at all. No calculations of NNL were made in this work.

LACUSTRINE SPAWNERS

Records for the construction of spawning habitat as compensation were available for two geographic areas, Lake Ontario and Snap Lake in NT. A spawning reef of 600 m^2 in area constructed in Lake Ontario was built as compensation for a large lake infill project (32 ha) associated with St. Mary's Cement located at Bowmanville, Ontario (Fig. 5). To assess spawning use by Lake Trout, 37 individual egg nets (Fitzsimons 1995) were buried in the reef by scuba divers prior to spawning and recovered after spawning had ended. No reference area was established for this work. Monitoring occurred over two spawning years but was only able to document limited spawning use the first year after construction. Although no spawning usage

was detected in the second year, this may have been influenced by the loss of over 50% of the collection gear. No calculations of NNL were made in this work

A single spawning reef was constructed in Snap Lake NT to compensate for the loss of an inland lake and its outlet stream in Snap Lake (NT) associated with development of a diamond mine. The reef was constructed of cobble that was assembled on the ice during the winter and allowed to sink to the bottom at ice out (Fig. 6). The reef, having dimensions of approximately 5 m wide by 20 m long, sits in water depths from 2 to 5 m. The objective of this reef was to provide spawning habitat for primarily Lake Trout but also round whitefish. A reference-impact monitoring approach was taken wherein 60 individual egg nets were buried by scuba divers on the artificial reef and at each of two natural areas that while appearing to have the requisite characteristics for Lake Trout spawning were not known spawning areas (Fig. 7). The location of Lake Trout spawning areas in Snap Lake prior to this work, were not known. Monitoring was able to confirm spawning at the artificial reef (35 eggs$\cdot$m^{-2}) but not at either of the two natural areas in Snap Lake. No calculations of NNL were made in this work.

MONITORING OF COMPENSATION

SPAWNING ACTIVITY

Fluvial spawners

The assessment of the effectiveness of spawning habitat restoration (SHR) for fluvial spawners has been related to numbers of spawners (House 1996, Klassen and Northcote 1988, Crispin et al. 1993, Gortz 1998), redd counts (Crispin et al. 1993, McInnis et al. 2008, Floyd et al. 2008, Klassen and Northcote 1988), and abundance of alevins (Palm et al. 2007, Floyd et al. 2008, Scruton et al. 2005). Each of these assessment methods has their advantages and disadvantages and for only one (alevins) can inferences be made about the quality of SHR. Although Roni et al. (2008) advocated that evidence of an adult response such as increased spawner escapement (e.g., number of spawners returning to a river), for projects focusing on the enhancement of spawning habitat, Korman and Higgins (1997) stated that in using spawner escapement time series data, there was less than a 50% chance of detecting a population response to habitat alteration unless the population change was large (more than a two-fold increase) or the post treatment monitoring period was long (>10 years). These authors stated further than an increase in statistical power may be possible by increasing the precision of escape estimates but that it would also be dependent on the magnitude of the population response to the habitat alteration, the duration of the monitoring and the extent of natural variability in abundance. Bradford et al. (2005) found a freshwater stock recruitment model to be more sensitive in detecting effects of habitat change when compared to measures of abundance for either spawners or smolts.

Counts of adult fish made prior to spawning while easily made by untrained observers, do not confirm actual spawning use which may be less than expected and/or occur elsewhere. Reliable redd counts which confirm that spawning has taken place, can be obtained with relatively little effort and training provided there are no water clarity issues, and if the area is not excessively remote and if so, can be accessed by aircraft. Redd counts provide a physical record of presumed spawning activity that can be readily enumerated within and among reaches of a stream and specifically address whether a specific section of habitat including compensation habitat has been used for spawning. For some species redd counts appear to be directly related to spawner escapement (Gallagher and Gallagher 2005). Although redd counts provide a higher level of certainty of the use of SHR than adult abundance, redd counts can be biased by test pits and redds are seldom excavated to confirm the actual presence and numbers of eggs

(McNeil 1964, Klassen and Northcote 1988). Some hatchery Atlantic Salmon will reportedly build redds but not deposit their full complement of eggs into a redd or fail to adequately bury the eggs released into a pit (Fleming et al. 1996).

Counts of fry and parr, usually obtained with electroshocking gear (Floyd et al. 2008) can also be used for assessing spawning habitat use and appear to be related to redd counts (Beland 1996). Emergence shows a high level of seasonal and diel dependence however (Gustafson-Marjanen and Dowse 1983), suggesting that temporally intensive sampling would be required to produce reliable estimates of emergence. In addition with increasing age of life stage evaluated, there is reduced likelihood that density is dependent on the quality of spawning habitat and instead there is an increasing likelihood that rearing habitat may be more important.

Lacustrine spawners

Discrete redds are generally not constructed by lacustrine spawners with the exception of Kokanee Salmon that may build redds if the size of substrate available is small enough (Hassemer and Reiman 1981). Otherwise most lacustrine spawners will use broadcast spawning where during spawning eggs are released over a relatively large area above the substrate, as occurs with Lake Trout (Esteve et al. 2008). Since redds are not constructed, the assessment of spawning activity by Lake Trout has involved a variety of active and passive collection gears (Fitzsimons 1996, Perkins and Krueger 1995, Fitzsimons 1995) to quantitatively assess egg density and confirm spawning activity. Because of the difficulty in obtaining reliable estimates of egg density with air-lifts post spawning, due to egg settlement especially in spawning habitat with deep interstices (Kelso et al. 1995), there was a shift in egg collection technology to traps deployed prior to spawning on the surface of the substrate (Schreiner et al 1995). However, because this gear proved difficult to anchor in place, was subject to failure, and was of unknown collection area because of irregularities on its surface and orientation, assessment of Lake Trout egg density now centers on the use of egg nets usually buried pre spawning in the substrate by scuba divers (Fitzsimons 1995, Perkins and Krueger 1995) but also with the potential for surface deployment when prefilled with substrate eliminating most of the problems associated with traps (unpublished data). Based on the limited data available, the density of eggs in egg nets appears to track the abundance of spawners (Fitzsimons et al. 2009b, R. M. Claramunt, Michigan Department of Natural Resources, pers. comm.).

Egg nets with some modification have been used by several investigators to assess variation in spawning between self-sustaining and non self-sustaining Lake Trout populations (Marsden et al. 2005), assess the effects of native (Fitzsimons et al. 2002, 2007, Claramunt et al. 2005) and invasive egg predators (Fitzsimons et al. 2009b) on egg survival, assess the effects of physical disturbance on egg survival and displacement (Fitzsimons 1995, Fitzsimons and Marsden 2014) and assess the dynamics of deep-water (25 m) spawning activity (Fitzsimons et al. 2006).

With respect to compensation habitat, egg nets have been used to assess the use of artificial reefs built as compensation habitat in Snap Lake (DeBeers) (Fitzsimons and Claramunt unpubl. rep.) and Lake Ontario (St. Mary's Cement) (EMG 2003). In addition egg nets were used to determine potential water drawdown effects associated with hydroelectric development in Nonacho Lake (Deze Energy) so as to determine the need for compensation habitat, and in Lac de Gras (Diavik) to assess the spawning use of artificial relative to natural spawning habitat to determine if additional compensatory measures were needed. (unpublished data). All of these activities were undertaken as part of an Authorization for a HADD and involved a single observational year and with no knowledge of predevelopment conditions. The two artificial reefs were constructed as out of kind compensation; the Snap Lake reef was constructed to compensate for the temporary loss of a small inland lake and stream, while the Lake Ontario reef was constructed to compensate for a large lake infill project. Although the Snap Lake work

was intended to apply a reference-impact approach, the two reefs used as references failed to yield detectable spawning such that the evidence of spawning on the artificial reef became the sole piece of evidence supporting the efficacy of the reef. No reference sites were used for the artificial reef built in Lake Ontario that yielded extremely low egg densities compared to densities for other reefs in the lake at the time (Fitzsimons 1995). The Nonacho Lake work revealed wide spatial variation in egg density within the lake which had experienced a 2 m increase in water levels in 1980 related to construction of a dam for hydroelectric generation. No reference lake was sampled for the Nonacho Lake work. Finally the Lac de Gras work was intended to apply a reference-impact approach using multiple sites for each of the categories. Despite this effort no egg deposition was detected suggesting either that egg density was so low as to be undetectable or that that Lake Trout were spawning elsewhere in the lake.

Egg collection nets are not without their biases and several studies have indicated that eggs can be lost from this gear post spawning leading to error in estimates of egg deposition (Fitzsimons et al. 2003, Claramunt et al. 2005, and Barton et al. 2011). The use of funnel-type gear buried in the substrate can provide greater protection of the eggs from current generated turbulence (McAughey and Gunn 1995, Barton et al. 2011, unpublished data). Such gear can also be sampled regularly either by scuba divers or surface operated pumps to determine temporal variability in spawning. Funnel-type gears however, tend to be difficult to deploy and the very traits that prevent the dislodgement of eggs may result in excessive sediment and algal accumulation requiring frequent disassembly of gear to clear collection tubes and funnels. In view of these problems and the existence of extensive data sets using conventional egg nets, artificial eggs released into nets just prior to spawning have been used to assess amounts of physical disturbance while at the same time providing a means for adjusting natural egg density for the effects of physical disturbance (Fitzsimons and Marsden 2014).

Emergent fry traps (Collins 1975) are another means by which Lake Trout spawning can be assessed. Due to a combination of mortality of embryos prior to the emergent fry stage and the possibility of lateral movement in the reef after hatch but before emergence, the density of fry tends to be one-tenth that of eggs. As a result, emergent fry traps are less able to detect spawning especially when spawning activity is low (Marsden et al. 2005). This combined with the difficulty in maintaining the gear in place once deployed, renders this gear less suitable for assessing spawning activity.

EMBRYONIC SURVIVAL

Although spawning habitat can be constructed and used by either fluvial or lacustrine spawners, for such habitat to contribute to recruitment it has to successfully incubate embryos up until the time that alevins leave the habitat. Accordingly, embryonic survival is one of the first lines of tangible evidence that spawning habitat rehabilitation has been successful given the caveats about earlier stages such as aggregation of spawners or redd abundance.

Measures of egg survival from which inferences of spawning habitat quality can be made, are possible using naturally deposited eggs for both fluvial and lacustrine spawners although several biases exist and some of these are more extreme for lacustrine spawners This reflects in part the nature of the spawning act, the habitat into which eggs are released, and the level of physical disturbance that eggs experience post spawning. Fluvial spawners build discrete redds within which the female buries eggs among multiple egg pockets at depths from 10-30 cm deep in the substrate (DeVries 1997). In contrast, lacustrine spawners like Lake Trout and some beach spawning Kokanee or Sockeye Salmon, broadcast eggs over a larger area dependent on substrate size. As a result until eggs settle into interstices they are highly susceptible to the effects of physical disturbance which can lead to high egg mortality (Fitzsimons 1995).

Apart from the effects physical disturbance resulting from natural causes the handling of eggs at early stages of development can also cause mortality because of the sensitivity of eggs to physical disturbance and this mortality may be completely unrelated to conditions in the spawning habitat (Fitzsimons 1994, Jensen and Alderdice 1989, Piper et al. 1982). Finally for both fluvial and lacustrine spawners the number of eggs spawned is mostly unknown. As a result using the number of naturally deposited eggs remaining post spawning can overestimate survival if there has been a substantial loss of dead eggs and alevins by decomposition, scavenging, predation, or gravel movement (Shaw and Maga 1943; McDonald 1960; McNeil 1964), a likely occurrence in many instances.

Fluvial spawners

To avoid some of the problems inherent in the use of the number and survival of naturally deposited eggs to infer habitat quality, various egg incubation devices using known numbers of embryos, have been developed that attempt with variable success to mimic the conditions experienced by naturally deposited eggs. Several methods exist for determining the survival of eggs of fluvial spawners *in situ* including Whitlock-Vibert boxes (Mackenzie and Moring 1988), specially modified egg bags (Pauwels and Haines 1994), or specially modified PVC tubes (Palm et al. 2007, Merz et al. 2004). Whitlock-Vibert boxes while completely permeable have been found in some studies however, to be subject to excessive sediment accumulation (Harshbarger and Porter 1979, 1982). Although the use of PVC tubes would have restricted the influx of fine sediments but also water movement, researchers using this technique located multiple windows along the length of PVC tubes and covered these with mesh of varying size (350-2000 μm) to maintain water flow. The mesh windows allowed some water movement but it appears it was inadequate based on egg survival. Egg survival using PVC tubes in the wild was extremely low (5-30%) and even in the hatchery survival was quite low (60%). In addition to the limitations on sediment accumulation and/or water movement, the boxes, bags and tubes used in these studies were all deployed in artificial redds. Due to their construction it would have been difficult to place these devices directly into a redd without disturbing the redd architecture which is probably important for maintaining water flow through the redd (Chapman 1988). However, the sediment composition and water quality of artificial redds may differ considerably from that of a redd built by a spawning female. For many fluvial spawning salmonines, a number of habitat factors, such as water velocity, water temperature, ground water seepage, sedimentation, and bottom substrate composition appear to influence survival and growth of embryos in a redd (Chapman 1988, Curry et al. 1994, 1995, Noakes and Curry 1995, Magee et al. 1996, Barnes et al. 2001, Bernier-Bourgault and Magnan 2002, Clement 2003, Curry and MacNeill 2004). Not surprisingly fluvial spawning salmonines select redd sites that are associated with stream characteristics leading to higher embryonic survival and growth (Magee et al. 1996, Bernier-Bourgault and Magnan 2002, Zimmer and Power 2006, Scott et al. 2005). Although females are able to modify the substrate composition during nest construction, typically removing fine sediments (Chapman 1988), such effects may be of relatively short duration dependent on the amount of infiltrating material present post spawning. Alternatively it may be the initial selection of habitat (e.g., pool-riffle transition) that is most important for maintaining adequate water quality for the duration of the embryonic period.

In view of the limitations of existing egg incubation methods a new method was developed (Fig. 8). With this method, almost the entire egg incubator, herein termed a capsule, is permeable to water as well as infiltrating sediments and by design can be injected directly into redds. Embryonic survival in capsules placed directly into redds is apt to be much more relevant to the effects of habitat quality on embryonic survival, than capsules inserted into adjacent but unused habitat. The capsule (Fig. 8) consists of a polypropylene mesh tube (5 mm square mesh; 7 cm dia, 20 cm length) having detachable porous (1000 μm) end caps which if required, could be

replaced with a collection device for collecting emergent fry (Fig. 8). The inside of the capsule was lined with 1000 µm Nitex mesh to prevent the loss of hatched fry but allow the infiltration of fine sediment. An egg and gravel (1-2 cm) slurry consisting of 100 hatchery brood stock eggs per capsule was added to the capsule which was sealed and transported to the river. At the river, a capsule insertion device (Fig. 8) was driven into the redd to the appropriate depth for naturally spawned eggs, usually 15 to 20 cm (DeVries 1997). The central rod used to drive the capsule insertion device was then removed while the outer tube of the capsule insertion device was held in place providing a void space in the substrate. An individual capsule was then placed into the void space in the outer tube and a rod used to hold the capsule in place while the outer tube was withdrawn from the substrate. Once complete, the capsule was not visible from the surface confirming burial. Its position was marked by a coloured string attached to the capsule prior to insertion allowing it to be readily found and removed at a later date. To assess the effects of holding eggs in the capsule and transportation effect on eggs capsules, a subsample of loaded capsules was subjected to the same handling as buried capsules and incubated under hatchery conditions and examined at the same time as capsules are removed from the river.

At the time of withdrawal from the substrate, capsules can be immediately frozen on dry ice and survival determined after the capsule contents are thawed. By freezing the capsule immediately after removal from the substrate, sediments entrained in the capsule during the incubation period are retained. Because of differences in particle size they are readily distinguishable from the gravel used to incubate eggs so can be separated out and used to conduct sediment analysis.

Using the above method to assess the suitability of redds constructed by hatchery Atlantic Salmon in the Credit River and Rodgers Creek (Ontario) a small tributary of the Credit River, it was evident that incubation of hatchery eggs in natural redds resulted in reduced survival relative to controls reared in the hatchery (Fig. 9). Moreover, the survival using known numbers of hatchery eggs reared in capsules resulted in a lower estimate of survival potential within an individual redd than survival based on naturally deposited eggs (Fig. 9). Although there appeared to some difference in survival of hatchery eggs in capsules between redds of wild and hatchery spawners (Fig. 10), both of these values likely overestimate true survival. The estimate of survival for eggs in capsules was always greater when based on the embryos remaining than when based on the initial number of eggs used (e.g., 100) (Fig. 11). Many factors likely contributed to the decline in embryo survival in capsules in the wild relative to capsules held in the laboratory and may involve water flow (Silver et al. 1963), dissolved oxygen (Meyer et al. 2008), and the amount and duration of exposure to fine sediment (Louhi et al. 2008, 2011). It was not possible to explain variation in survival either to hatch or to the live fry stage at the time capsules were recovered based on the proportion of fine sediment alone (Fig. 12) suggesting multiple factors need to be measured to account for variation in survival. Alternatively it's not known when sediments were entrained into capsules and variability in the period of entrainment and concurrent exposure of eggs may explain some of the variation in survival relative to sediment composition.

Lacustrine spawners

The availability of methods for assessing the suitability of the interstitial environment for supporting successful embryonic development are more limited for lacustrine spawners like Lake Trout, compared to fluvial spawners (Manny et al. 1995). For lacustrine spawners current methods involve incubating eggs in plexiglass incubators containing 50 cells with each cell holding one egg. Although the incubators are buried in the substrate by scuba divers, the design of the incubators does not preclude the movement of eggs. Results obtained by Manny et al (1995) indicated that wave energy may be just as important as sediments in controlling egg survival. In addition, due to limitations of the methods currently available (Manny et al. 1989,

1995, Eshenroder et al. 1995), results obtained may not necessarily reflect conditions in spawning habitat and instead reflect the sensitivity of eggs, when first deployed, to the effects of physical disturbance (Fitzsimons 1994)

MEASUREMENT OF FACTORS CORRELATED WITH EGG SURVIVAL

Various habitat measures related to egg survival (fines, oxygen, ammonia, physical disturbance (Chapman 1988, Garside 1959, Sly 1988, Fitzsimons et al. 2007, Fitzsimons and Marsden 2014) and embryonic fitness (Fresh and Schroder 1987, Lohi et al. 2011) have been measured in spawning habitat. These have been applied both to fluvial and lacustrine spawners and thus may be relevant for assessing the suitability of compensatory habitat for supporting spawning and embryonic survival even in the absence of measures of egg survival. The relevance of the results though to wild populations are unclear however, since no wild Lake Trout spawned at the sites used that were selected on the basis of criteria thought to be important to Lake Trout.

Foremost among factors known to affect embryonic survival and fitness for fluvial spawners is substrate composition, particularly the amount of fine material present (Chapman 1988). Recent work indicates that the finest material (<125 µm) may be responsible for the greatest decline in survival and at a relatively small percentage of the sediment present (Louihi et al. 2008, 2011) Threshold values for sediments 125 µm and smaller ranged from 0.2 to 1.5% (Lapointe et al. 2004, Levasseur et al. 2006, Julien and Bergeron 2006). Rarely though can measures of sediment composition and embryonic survival in the wild be directly correlated since measure of each are made in different habitats. One of the few methods available to measures sediments and embryonic survival in the same habitat used an infiltration cube wherein embryos were reared in an artificial redd in natural substrate and survival of seeded eggs related to the sediment composition of the sediment infiltrating the area containing the eggs (Levasseur et al. 2006). This method because of the relatively large size of the infiltration cube (30 x 30 cm) and related equipment used, allowed the collection of large amounts of sediment for analysis, but is considered inappropriate for application to redds due to the marked alteration in redd composition deployment of such gear would involve. The capsule method described above while capable of measuring fine sediment infiltration, provides low yields particularly of fine sediments (< 2 g) and this may limit the precision of estimates and development of predictive relationships between substrate composition and embryonic survival.

Ammonia is extremely toxic to early life stages (Burkhalter and Kaya 1977), and can accumulate in spawning habitat under anoxic conditions (Sly 1988). Dialysis containers (Sly 1988) can be used to track the buildup of ammonia which can be related to embryonic survival. Despite the availability of methods to assess ammonia build-up on spawning reefs and a knowledge of toxic levels there are few measurements of ammonia at Lake Trout spawning reefs limiting an assessment of its importance (Sly and Evans 1996).

Egg displacement can result from the movement of the substrate comprising a spawning reef or alternatively when the substrate remains in place, the movement of eggs. Kelso et al. (2005) reported the movement and destruction of a natural Lake Trout spawning reef in Lake Superior. In Lake Michigan the partial burial of egg collection nets under two to three layers of cobble on the leeward side of a natural spawning reef, suggested that in some circumstances, the movement of spawning reefs may be ongoing, dependent on the intensity of storm driven currents (Jonas et al. 2005). Given these observations, it is not surprising that some artificial reefs if incorrectly sited may be moved or be destroyed. An artificial reef used for Lake Trout spawning in eastern Lake Ontario (T. Stewart, OMNR, pers. comm.) and sitting in 1 m of water, was completely displaced onto shore by fall storms (unpublished observations). There was however, no evidence that the artificial reefs constructed as compensation in Lake Ontario (EMG) and Snap Lake (Fitzsimons and Claramunt unpubl. rep.) showed any evidence of

movement. The observations for Snap Lake were consistent with the near total recovery of artificial eggs from this reef. This contrasts with the high level of artificial egg loss at a reef in Lake Champlain which averaged 63% where currents slightly less than those observed in the Great Lakes (Fitzsimons and Marsden 2014). Accordingly the use of artificial eggs (Crisp 1989) may be an effective means of determining the amount of physical disturbance at artificial reefs relative to adjacent natural spawning habitat.

CONCLUDING REMARKS

Habitat restoration practitioners have several methods at their disposal for assessing the success of compensatory habitat intended for the creation, rehabilitation, or restoration of spawning habitat. This applies to both fluvial and lacustrine spawners. Many of the methods do not require a high level of technical knowledge to implement but may be labor intensive in the short and long term possibly limiting their use and ultimate effectiveness. The real challenge for practitioners is in integrating information obtained on the effects of compensation over a small geographic area and which may be of limited relevance to population success, to other measures (e.g., escapement, recruitment) that may be spatially and temporally removed from the compensation habitat but in the long-term more relevant to population status. Furthermore while it may be difficult to relate these other measures to specific compensation measures, they may be extremely important to population success and have a long history of use. Additional challenges exist for practitioners in northern environments where little is known of baseline conditions. This makes it extremely difficult to identify reference habitats for comparison with artificial habitats. Moreover even when practitioners are successful in identifying reference habitats, their understanding of the full suite of environmental factors impinging upon these reference habitats may be limited confounding the assessment and evaluation of artificial compensatory habitat.

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FIGURES

- Spawning adults
- Redds
- Eggs
- Fry
- YOY
- Returning adults

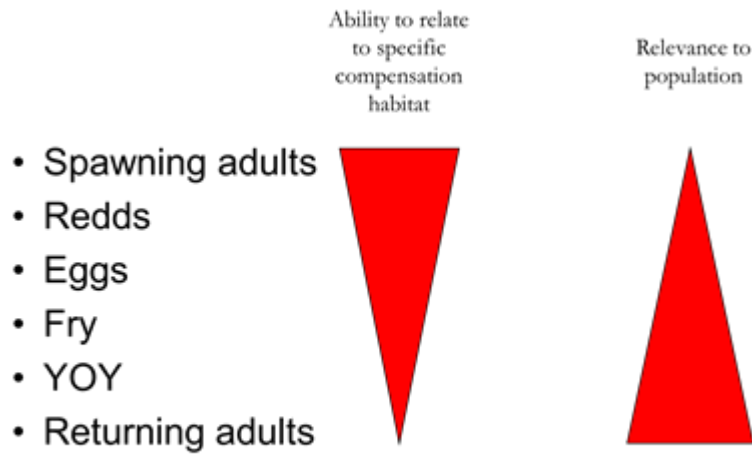Ability to relate to specific compensation habitat

Relevance to population

Figure 1. Schematic to contrast the declining ability to relate the effects of compensation habitat targeting early life stages to subsequent life stages which by comparison are generally of higher relevance to population status.

Figure 2. Type I spawning channel in Yukon River at Whitehorse (YT) looking upstream (top panel) and downstream (bottom panel).
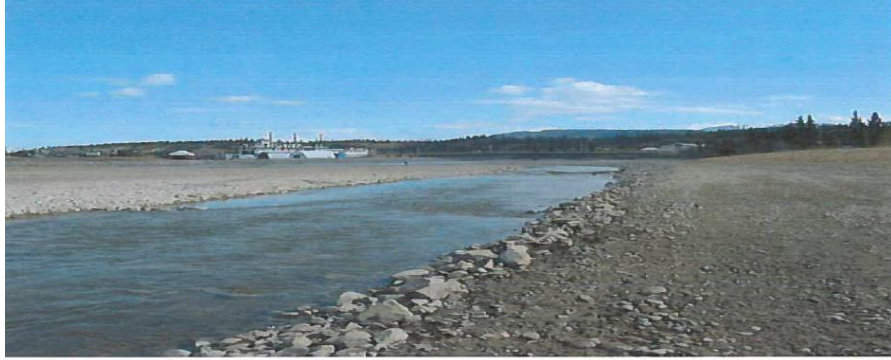
Figure 3. Type II spawning channel in Yukon River at Whitehorse (YT) looking upstream (top panel) and downstream (bottom panel).
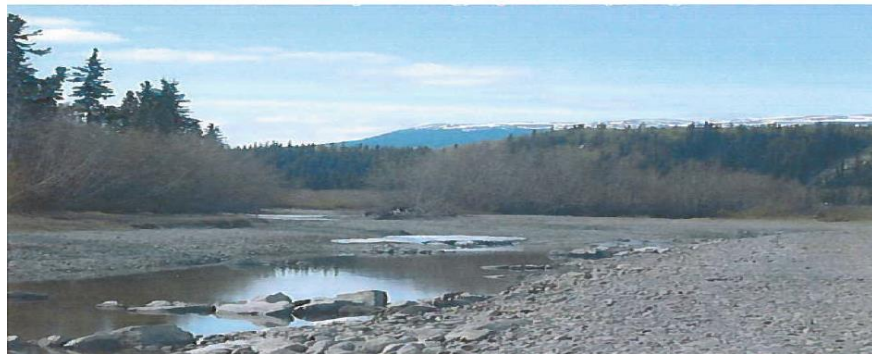
Figure 4. Type III spawning channel in Yukon River at Whitehorse (YT) looking upstream (top panel) and downstream (bottom panel).
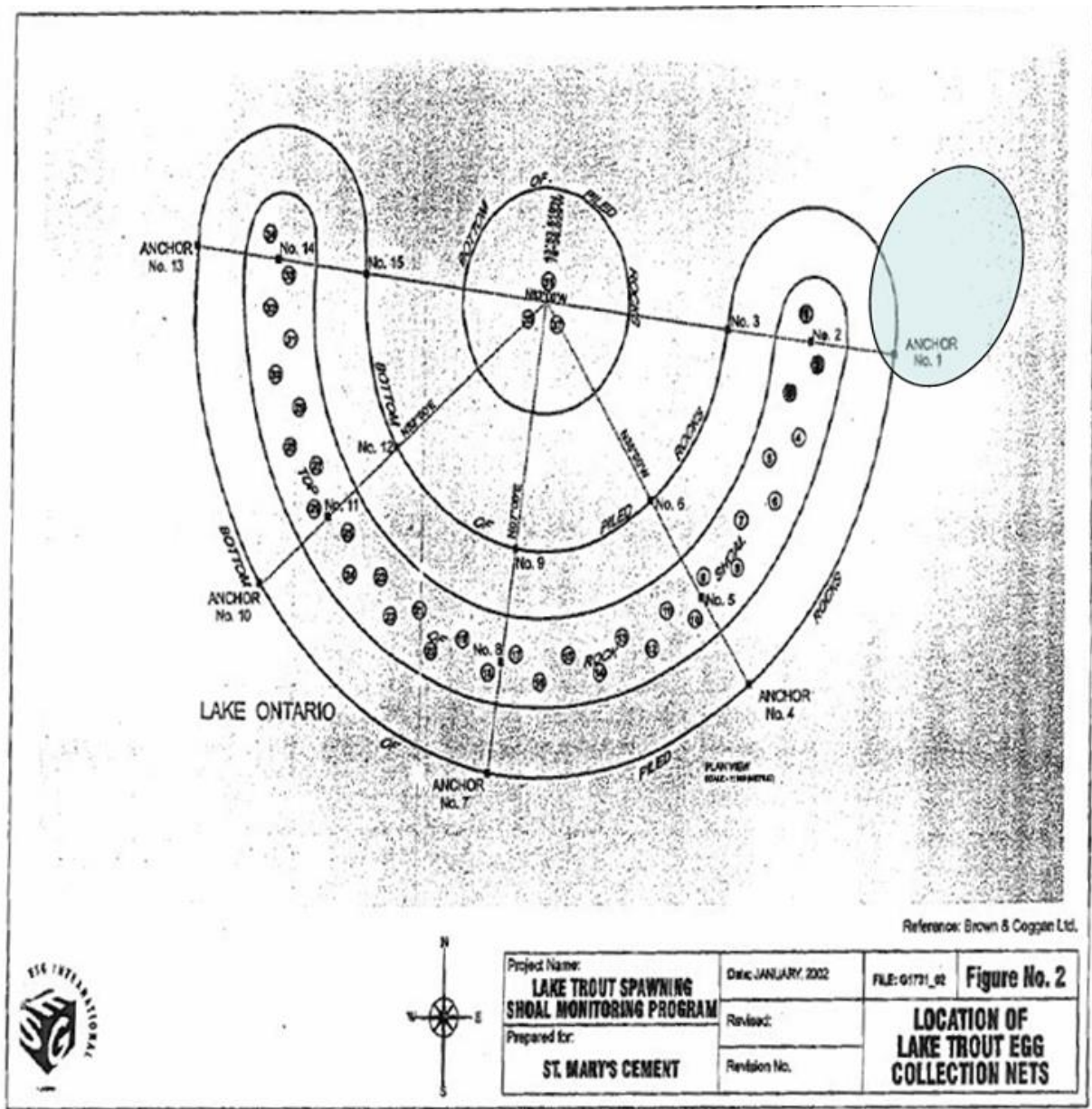
Figure 5. St. Mary's Cement Lake Trout Spawning Shoal. Highlighted area shows extent of spawning occurring in 2001. No spawning was detected in 2002.

a)

b)

c)

Figure 6. Snap Lake showing a) the transport of rock out onto the ice, b) the final reef profile on the ice and c) the initiation of the reef subsidence at ice out.

a)

b)

Figure 7. Snap Lake showing egg collection nets in situ at a) the artificial and b) one of the natural reefs.

Figure 8. Details of a) egg capsule injection device disassembled with a capsule, b) assembled egg capsule injection device, and c) egg capsule with emergence collection net attached and sample of substrate used.
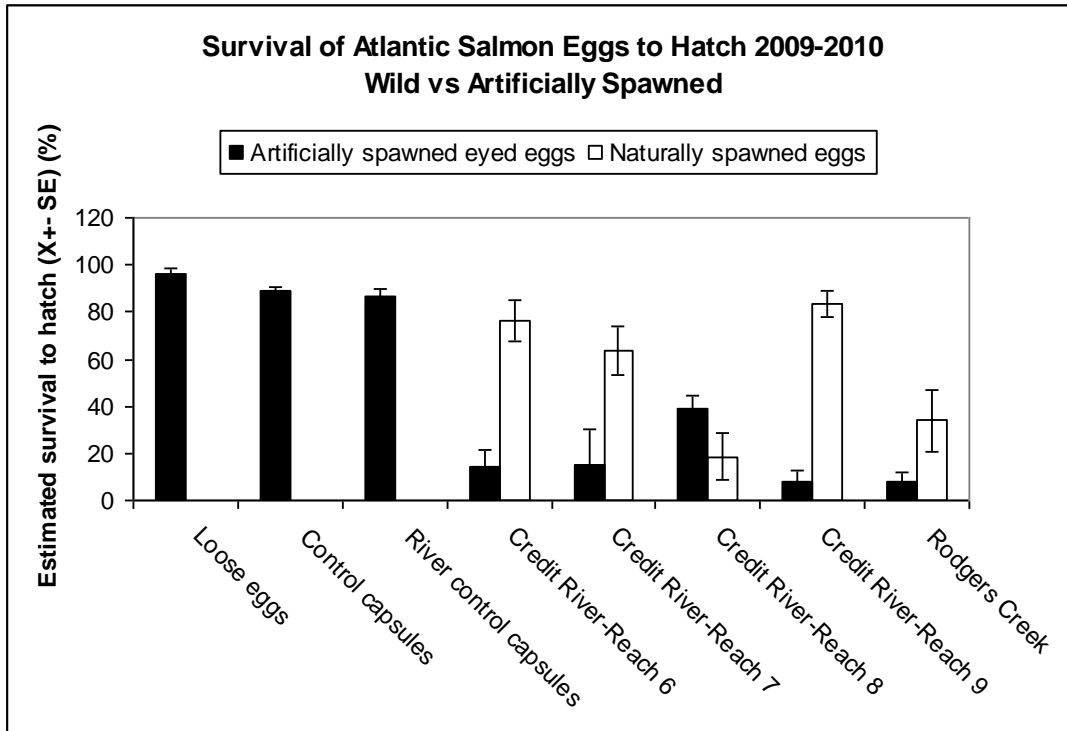
Figure 9. Comparison of survival of Atlantic Salmon eggs in capsules in controls relative to eggs in capsules and eggs excavated from redds in the Credit River and Rodgers Creek.
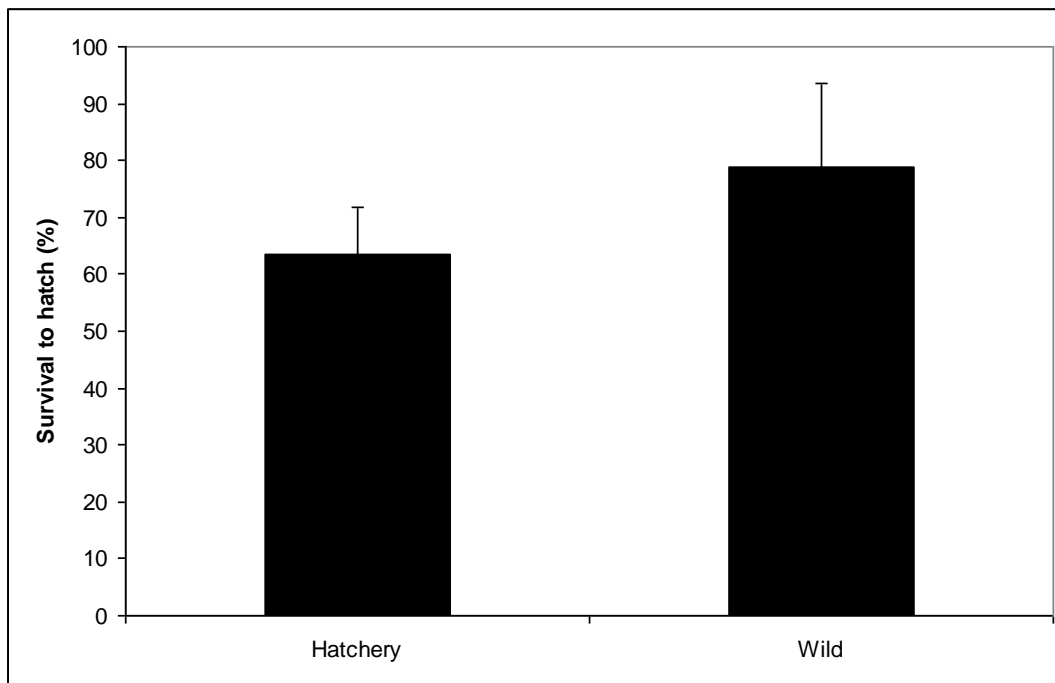

Figure 10. Mean survival to hatch of Atlantic Salmon eggs in capsules injected into Atlantic salmon redds built by either hatchery or wild spawners.
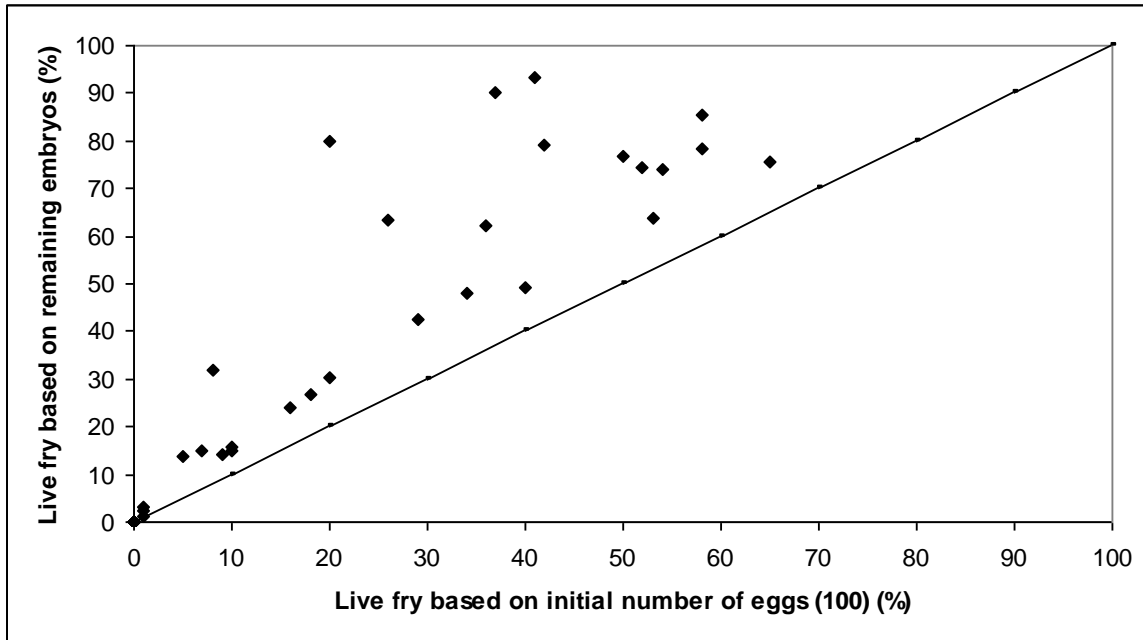
Figure 11. Relationship between survival of eggs to the fry stage based on embryos remaining relative to survival based on the initial number of eggs used.
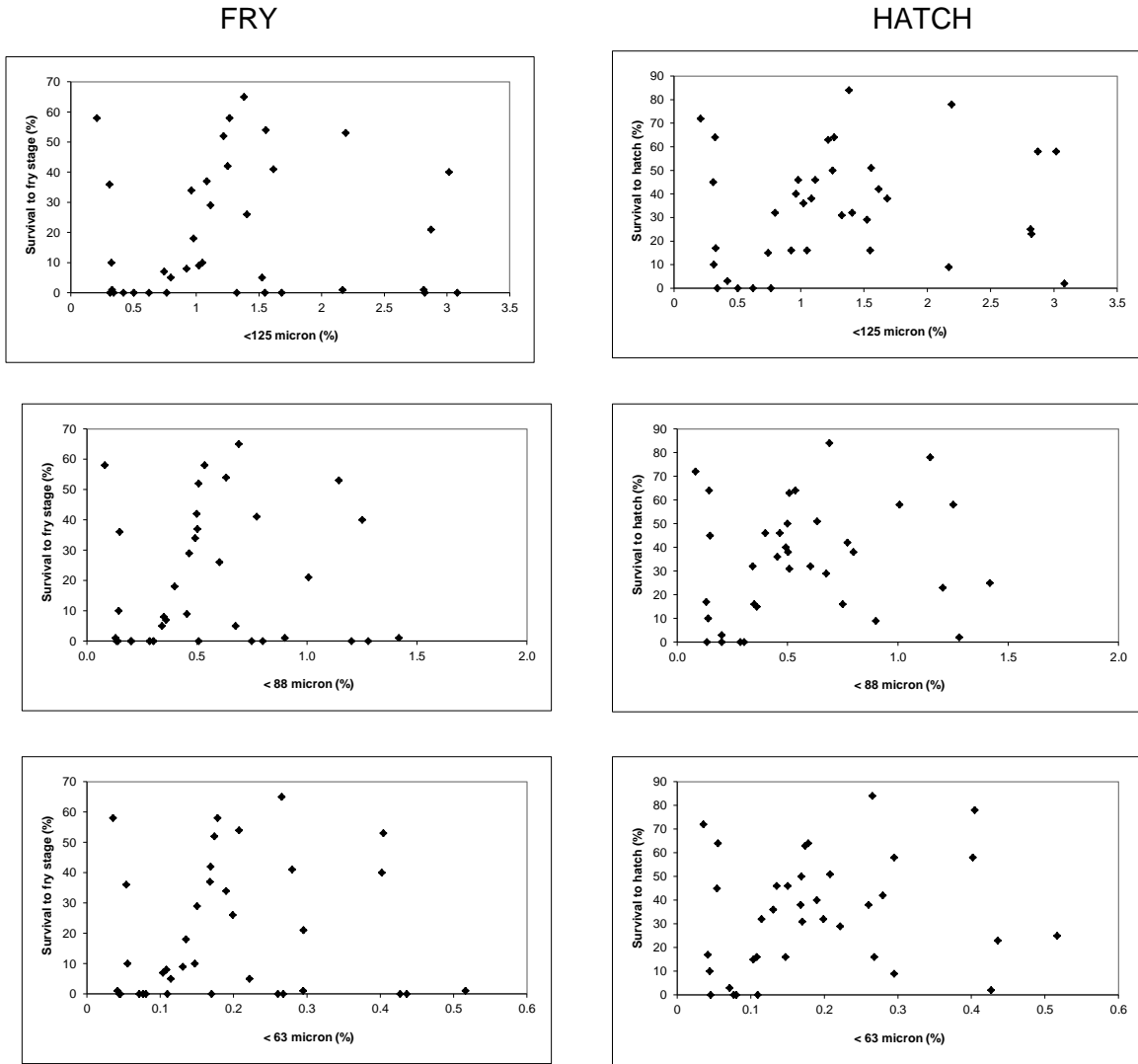
FRY

HATCH

Figure 12. Comparison of Atlantic Salmon egg survival in egg capsules to the fry or hatch stage relative to infiltration (%) by three successively smaller sizes (a) <125, b) <88 and c) <63 micron of fine material.