A review and risk analysis on potential impacts of riverine recreational activities on Atlantic Salmon (*Salmo salar*) in eastern Canada

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Abstract

Atlantic salmon populations face a number of significant, human-driven threats such as overfishing and thermal stress from anthropogenically-accelerated climate change. A considerable body of research has been devoted to such large-scale threats as well as catch-and-release fishing, while the potential impacts of other recreational activities on Atlantic salmon while in rivers have been largely overlooked. Here, we undertook a systematic literature review of the effects that recreational activities (excluding direct impacts of catch-and-release angling) might have on the welfare and survival of Atlantic salmon in riverine systems at all relevant life history stages. Examples of relevant activities examined here include swimming, all-terrain vehicle (ATV) use, and underwater photography. We also performed a relative risk assessment of such activities based on the likelihoods of their occurrence and the severities of their potential impacts. For the most part, the impacts of non-angling recreational activities on Atlantic salmon are likely widespread but largely temporary. Redds, eggs, and juveniles were generally found to be more susceptible to most threats than smolts and adults. However, some activities have significant destructive potential such as ATV use in or around spawning habitats. Significant risks also remain concerning pathogen and invasive species transfer via angling gear, waders, canoes, and other equipment that may be moved across systems without proper cleaning. Although we focused primarily on risks to native Atlantic salmon populations in eastern Canada, the risk assessment framework developed here is broadly applicable and easily adaptable for management in other contexts and jurisdictions with populations of riverine Atlantic salmon and potentially other migratory salmonids too.

Keywords: Anthropogenic impacts; Conservation; Freshwater fish; Management; Recreation; Salmon

1. Introduction

The Atlantic salmon (*Salmo salar*) is an ecologically, economically, and culturally significant fish species throughout much of eastern Canada (Nettle 1857; Parenteau 1998; VanderZwaag et al. 2011; Gardner Pinfold 2011) and many other countries on the North Atlantic Ocean, with populations hosted in over 2000 rivers across its native range (Chaput 2012; Myrvold et al. 2019). Landlocked or non-anadromous populations are also found across eastern North American and Northern Europe (Hutchings et al. 2019). Over the last several hundred years (i.e., during colonisation of North America by European settlers and the development of more advanced fishing technologies), these fish have been subjected to a number of deleterious anthropogenic disturbances and impacts. Sources of disturbances include commercial fisheries (although partial or full moratoria on commercial harvests have since been implemented across eastern Canada between 1984-2000; Pardo et al. 2021; Ireland in 2006; Brennan and Rodwell 2008; and Norway in 1989; Jensen et al. 1999); climate change (Jonsson and Jonsson 2009; Thorstad et al. 2021); aquaculture (Keyser et al. 2018, Sylvester et al. 2019); and, significant habitat alterations and migration barriers such as hydroelectric dams (Scruton et al. 2008). Despite increasing levels of protections at multiple levels of government over recent decades, many populations of Atlantic salmon remain far below historical, sustainable levels. As a notable example, Lake Ontario Atlantic salmon were extirpated by the end of the 19th century, likely due to a combination of factors including overharvesting, pollution and runoff from land development and industry, negative effects of restocking efforts on wild population genetics, and other major changes in ecosystem dynamics such as invasive species and temperature warming as shade trees were converted to agricultural crops (Dymond et al. 2019; Morrison and Peiman 2022). Among extant populations, there is usually little to no evidence of recovery even after several decades of relief from commercial fishing pressures, and there is sometimes evidence of continuing declines (Chaput 2012; ICES 2021; Pardo et al. 2021). The Committee on the Status of Endangered Wildlife in Canada (COSEWIC) released a report assessing the conservation statuses of regional populations of Atlantic salmon throughout Canada, which has not been updated in over a decade. Of the 16 populations COSEWIC identified, five were considered "Endangered", four were considered "Special Concern", and one was considered "Threatened", while the remaining populations assessed were considered either "Not at Risk" (four), "Data Deficient" (one), or "Extinct" (one; COSEWIC 2010). Although our focus here is on Canada, Atlantic salmon are in jeopardy across their native range.

In the face of such large-scale anthropogenic impacts on Atlantic salmon, little to no attention has been given to how Atlantic salmon may be impacted by smaller-scale human recreational activities that occur in rivers where these fish are present and may superficially be deemed to be benign. Most research on non-angling recreational activities focuses on fish in popular ecotourism destinations, particularly places such as coral reefs or freshwater systems in lower latitudes (e.g., Bessa et al. 2014; De Brauwer et al. 2019; Riniwati et al. 2019). In the case of Atlantic salmon in Canadian rivers, direct impacts (e.g., physical disturbances to the fish) and indirect impacts (e.g., water contamination from sunscreen, alterations to habitat structure by recreationists) from activities such as canoeing, snorkelling, and underwater photography could potentially be harmful to the fish or their environments.

Atlantic salmon eggs are laid in gravel stream beds in late fall, hatching in early spring and developing into parr that spend 1-8 years in the stream before smoltification and downstream migration to the sea (Aas et al. 2010; Thorstad et al. 2021). The salmon feed and grow in the ocean until they reach sexual maturity and return to their natal streams to spawn. Unlike Pacific salmon (*Oncorhynchus* spp.), Atlantic salmon are iteroparous, and adults that survive their spawning (kelts) return downstream to the sea until the next viable spawning season (Hubley et al. 2008). Thus, non-angling recreational activities may pose threats to eggs, juveniles, and adult fish depending on the time and place as well as the nature of the activity. Moreover, different life history stages may not be equally sensitive to various stressors. For example, potentially acute toxic effects of sunscreen ingredients may be more impactful on low-mass juvenile parr than large, fully-grown adults. Population effects of mortality also vary among life stage which has implications for risk of different stressors. For example, juvenile Atlantic salmon are subjected to density-dependent mortality (typically from factors such as predation and competition for space and food), while mortality in Atlantic salmon at sea is density-independent and largely mediated by environmental factors (Jonsson et al. 1998). Hence, human activities causing extra mortality at the earliest life stages may have relatively small impacts in terms of reduced number of spawners as these could potentially alleviate some intra-specific competition and therefore increase survival for the remaining fry and parr, whereas extra mortality at the smolt stage and later will have a more direct negative impact on the number of spawners. Regional and jurisdictional differences in the prevalence or permissibility of recreational activities are also highly relevant, as explored in more detail below.

This review was conducted with two main purposes in mind: first, to review the available literature on the potential effects of non-angling recreational activities on Atlantic salmon and their freshwater habitats, and second, to present a risk analysis highlighting which activities may or may not be most likely to adversely affect Atlantic salmon present in Canadian rivers. The risk assessment focuses exclusively on the relative impacts of non-angling recreational activities and does not include relative risks with respect to climate change, overfishing, fragmentation (e.g., dams), and other large-scales stressors that fall outside the scope of this work. The risk assessment is also more broadly relevant to Atlantic salmon across their range but given regional differences in river characteristics, biology, and human use patterns, it would need to be customised for optimal relevance to another region (or even from watershed to watershed). Our review did not include some recreational activities that, while being valid sources of disturbance for Atlantic salmon and other fishes, have been recently reviewed or assessed elsewhere such as boating and other sources of noise pollution (e.g., Mickle and Higgs 2018) and the direct aspects of recreational angling such as catch-and-release (Van Leeuwen et al. 2020), and their impacts might be particularly variable in time and space depending on, for instance, the applied fishery management rules. We do, however, assess indirect effects pertaining to angling (e.g., plastic pollution) as these metrics are generally not included in angling stress literature. A full list of considered activities is provided in Box 1. Search protocols and strategies are detailed below in the methods section.

2. Literature Search Approach

A literature search was conducted using the Web of Science Core Collections (WoSCC) database on April 11 2022 with the following search string: TS=((salmon OR salmon* NOT salmonella) AND (lake$ OR river$ OR stream$ OR freshwater OR “fresh water”) AND (recreatio* OR touris*)). The search engine Google Scholar was also used to supplement the WoSCC searches and locate articles not specific to salmonids using generic terms like “fish” and keywords relevant to recreational activities of interest (Supplementary File 1).

To identify grey literature (e.g., government/industry reports) simplified search strings were used to search relevant organisational websites. French and English websites were searched, and the full list of websites and search terms can be found in Supplementary File 1. Targeted emails were also sent to salmonid specialists requesting any primary or grey literature they may be aware of describing the impacts of non-angling recreational activities on Atlantic salmon, though this failed to yield any relevant results included here.

The search results from WoSCC (994 articles) were initially screened at the title and abstract level in Endnote online (Clarivate, London, UK) and then at the full-text level. Articles were eligible for inclusion in the review if they described (quantitatively or qualitatively) the influence of non-angling recreational behaviours on Atlantic salmon and/or Atlantic salmon spawning habitat. However, if articles detailed similar relevant phenomena in other salmonids or other fishes in general, they were also included and used to supplement the Atlantic Salmon literature. Ultimately, 48 of the 994 articles passed screening at the title and abstract level, and of those only 16 were considered sufficiently relevant for inclusion when screened at the full-article level.

3. Findings on Direct Impacts of Recreational Activities/Stressors on Atlantic Salmon or Other Salmonids

3.1 Habitat Characteristics and Recreation-Oriented Alterations

Humans may degrade shorelines when creating and extensively using pathways and other access routes to streams and rivers, primarily through altering habitat structure and plant communities, and specifically the removal or movement of woody debris and natural structures that can provide useful habitat for juvenile and spawning adult salmon (Lewin et al. 2006; Floyd et al. 2009). Restoration of stream habitat by adding woody structures may help mitigate such impacts in the event of damage from human access and use, but this is not always the case (Riley and Fausch 1995; Nislow et al. 1999). Proactive management and the conservation of natural habitat would be preferable to reduce the risk of degradation or loss of habitat elements that are beneficial for Atlantic salmon.

Certain habitat characteristics associated with good quality salmonid habitat in rivers and streams (e.g., flow rates) may coincide with desirable water characteristics for activities such as white-water rafting and kayaking (Carolli et al. 2017). These conditions are most typical during springtime and early summer when snow is melting, when salmon smolts are initiating the seaward migration and adult fish are beginning to return from the ocean. If stream habitat is altered to facilitate white-water rafting (primarily through creating physical structures that concentrate and increase stream flow in certain areas such as weirs or wing dams), these practices may impede the movement of salmonids and other fishes if they are not large or strong enough to overcome the physical obstacles at extremely elevated flow rates (Fox et al. 2016). The pools in habitats modified for white-water recreation likewise appear to be less suitable for salmonids than natural pools, potentially holding lower numbers and densities of salmonids (Kolden et al. 2016). Wing dams and weirs placed in rivers to create artificial pools alter sediment transport in rivers and with time are likely to eliminate spawning and rearing areas, though such habitats may be restored with removal of the structures (Pulg et al. 2013; Pulg et al. 2022; Gebreegziabher 2023).

3.2 Wading, Vehicles, and Watercraft

Human activities that involve standing on the substrate of streams and rivers, or the movement of vehicles through shallow streams and rivers, can destroy habitat and salmon eggs if redds are present. In a similar context, one of the highest threats to common grayling (*Thymallus thymallus*) eggs in France is the degradation of eggs by wading anglers as the presence of its eggs in French rivers coincides with trout fishing season opening (Keith et al. 2011). Thus, wading could be a threat to Atlantic salmon if its spawning habitats are not protected from wading when eggs are present. On the other hand, wading is more likely to occur in warmer summer months when redds and eggs are not present given that salmon tend to spawn in autumn and eggs hatch in the following spring. Wading during the spring and autumn may therefore most likely be a concern for anglers fishing in-stream, and less of a concern for bathers/swimmers who are more abundant in the summertime. This concern also applies for places where angling is permitted at where eggs and redds are likely present; in most Canadian Atlantic salmon rivers, angling is only allowed from June to September, where eggs and redds are absent (Quebec Fishery Regulations (SOR/90-214), Newfoundland and Labrador Fishery Regulations (SOR/78-443), Maritime Provinces Fishery Regulations (SOR/93-55)). In one experiment, wading even once over the eggs of brown trout (*Salmo trutta*), rainbow trout (*Oncorhynchus mykiss*), and cutthroat trout (*O. clarkii*) reduced survival of a redd by almost half (43% mortality), and two passes by a wading person could nearly eliminate an entire redd (96% mortality; Roberts and White 1992).

Atlantic salmon redds can often be built at depths of < 30-40 cm (DeVries 1997; de Gaudemar et al. 2000), well within the range in which threats from all-terrain vehicles (ATVs), mountain bikes, horseback riding, etc. remain plausible should trails lead near or through spawning grounds in shallower waters. We are unaware of any published primary literature on ATVs, mountain bikes, canoes, kayaks, other vehicles/watercraft, or horses being driven/ridden over redds, yet non-governmental organisations, news outlets, and government sources have published comments or articles on issues such as heavy canoe traffic and ATVs (and even sport utility vehicles) driven through rivers during low-water periods (e.g., Atlantic Salmon Federation 2021; CBC News 2021), damaging habitat, disturbing parr and other fishes, and releasing clouds of sediment into the water. It stands to reason that the impacts of such activities on redd integrity and survival could be catastrophic in small creeks and tributaries where salmon may spawn. However, most of these spawning areas are unexposed during the egg rearing season because they are in deeper, fluvial areas and eggs are buried from early winter through springtime when ATVs are less active. There may also be additional protection afforded by ice cover in rivers in higher latitudes. Reports from perceived risks of ATVs and habitat destruction with relation to hunting and angling, particularly in wetland habitats, are not new (e.g., Government of Newfoundland and Labrador 1999). More troubling for salmon is the potential sedimentation caused by driving through rivers; ATVs and other vehicles can cause bank erosion and activate sediments that smother habitat and small fish downstream. Spawning areas may be clogged by sedimentation downstream of river crossings where sediments are activated by driving through the river. Shelter for fry and parr can also be lost when banks collapse or sediments fill pores used by small fish.

3.3 Littering, Pollution, and Potential Toxicological Effects

We investigated possible effects of litter and pollution that could be present as a by-product of recreational activities occurring in salmon rivers. Ultimately, we found no tangible evidence of such detrimental impacts in Atlantic salmon, but identified knowledge gaps that do warrant some discussion. Fishing inevitably leads to some degree of littering or pollution, as lures, sinkers, and other forms of tackle are accidentally lost to fish or snags over time. In one study of tackle loss in five Minnesota lakes between May and October 2004, it was reported that approximately one tonne of lead tackle was accidentally lost during this period alone (Radomski et al. 2006). The toxicological effects of discarded lead tackle have been studied extensively in birds, rarely in mammals and reptiles, and apparently never in fish and amphibians (Grade et al. 2019), and so it is not yet known to what degree lead waste may affect salmonid health in streams and rivers. Salmon routinely ingest fishing lures and flies containing hard plastic and metal hooks, but it is not known what if any toxicological effects this may have. There is relatively more research on the ingestion of soft plastic lures (SPLs) in other salmonids (e.g., Raison et al. 2014), but this is not likely an issue as SPLs are ineffective and rare for salmon fishing and only artificial flies are permitted on most Canadian salmon rivers (Newfoundland and Labrador Fishery Regulations (SOR/78-443), Quebec Fishery Regulations (SOR/90-214), Maritime Provinces Fishery Regulations (SOR/93-55)).

Another source of chemical pollution linked to aquatic recreation is ultraviolet (UV) filter leaching from sunscreens and cosmetics that humans apply prior to engaging in recreational activities in water bodies. We found no evidence on the extent and potential toxicological impacts of UV filters in salmonids at naturally relevant concentrations, and whether such concentrations are even reached in salmon watersheds. This was included in our review as a plausible concern as many UV filters (e.g., benzophenone-3 [BP-3]) are estrogenic (i.e., capable of mimicking estrogen or interfering with estrogen dynamics in living organisms), lipophilic, and capable of bioaccumulating in many fishes including salmonids (Balmer et al. 2005; Fent et al. 2010; Vandergrift et al. 2022). UV filters may also be able to disrupt endocrine function, damage DNA, and induce oxidative stress, at least in smaller fishes such as zebrafish *Danio rerio* and guppies *Poecilia reticulata* (Blüthgen et al. 2012; Liu et al. 2015; dos Santos Almeida et al. 2019).

Other recreation-linked chemical pollutants include the broad array of ingredients in insect repellents, cosmetics, hygiene products, medicines, and other substances used or consumed by humans in and around water bodies (Battaglin et al. 2018). These contaminants enter water bodies directly from humans (leaching off of humans, excreted in urine/faeces) or indirectly (e.g., runoff or wastewater from campground facilities and other recreational facilities) and, like many UV filters, can act as endocrine disruptors in fish (Battaglin et al. 2018). However, we are not aware of any attempts to quantify these in recreation-prone salmon habitats and whether any of these contaminants actually occur at biologically relevant concentrations, which will depend largely on the extent/intensity of recreational activities occurring.

3.4 Human Presence and Disturbances to Individual Fish

We considered the above and other, direct human interactions with Atlantic salmon representative of ecotourism (e.g., swimmers, snorkellers) in our searches because such interactions with a variety of recreational users continue to be of significant public concern in Canadian communities living near riverine habitats supporting Atlantic salmon (e.g., Desmeules 2007; Beauchesne 2016; Gagné 2019; Bilodeau 2022; Langlois 2023). However, these other interactions appeared to be largely unstudied in this context and unlikely to manifest as more than brief stressors to these fish. This was a plausible concern as, in non-extractive tourism and recreation, animals may experience stressful or intensive interactions with humans that, in effect, mimic predation risk scenarios and prevent fish from exhibiting necessary, normal behaviours for survival such as feeding and reproduction (Albuquerque et al. 2014; Bessa and Gonçalves-de-

Freitas 2014). Juvenile salmon are at risk of predation from mammals, birds, and other fishes (Mohler et al. 2002; Flávio et al. 2021), and extensive human intrusion in their habitats could induce short-term stress responses and flight behaviours in nearby individuals. Theoretically, repeated interactions can reduce the long-term frequency of anti-predator behaviour via habituation to human presence, translating to a failure to respond to predators once humans leave (Geffroy et al. 2015), but in this context would require considerable degrees of human disturbance.

We did not identify any literature on potential effects of swimmers, snorkellers, or divers on the stress or welfare of individual Atlantic salmon or other salmonids. In other contexts (e.g., scuba), diving may trigger species- and size-dependent runaway or hiding responses (Iborra 2022). Short-term flight responses (e.g., swimming away up- or downstream, or hiding amidst structures and crevices for juveniles; Heggenes et al. 1993; Orell and Erkinaro 2007; Orell et al. 2011) have been observed in response to human presence, especially with sudden or significant movements, in the context of snorkelling surveys and drift diving, wherein a diver swims upstream against the current or drifts downstream with the current, respectively. These are common practices in salmonid research and sampling methods for data such as individual counts and size class data, and identifying wild vs. cultured fishes at various life stages (Heggenes et al. 1993; Whalen et al. 1999; Orell and Erkinaro 2007; Mahlum et al. 2019; Skoglund et al. 2021). Given that repeated surveys in systems with high visibility are capable of generating similar fish counts and therefore observing at least many of the same individuals over multiple sampling efforts (e.g., Orell and Erkinaro 2007), the disturbances caused by passing swimmers in the context of snorkelling surveys or drift diving appear to be transient and do not likely interfere with habitat use for a long period of time. How the effects of brief appearances by a small number of swimmers compare to those of more swimmers present for longer periods of time (i.e., recreational swimmers) is uncertain given the lack of data on the latter topic. In summertime, parr exhibit territoriality in stream habitats not far from the redds in which they were spawned (within ~1-5 m) and engage in territorial defence primarily during the day (Keenleyside and Yamamoto 1962; Gustafson-Greenwood and Moring 1990). Pre-spawning migrating adults in rivers and streams do not exhibit territorial behaviour (Keenleyside 1962) and are capable of fleeing disturbances as evidenced by observations from snorkelling surveys and drift diving, so they may be much less likely to be adversely impacted by human presence in the water in the absence of other interacting stressors and threats (e.g., angling, anthropogenic barriers to migration).

It may be reasonable to assume that the above also applies to the passing of non-motorised watercraft such as canoes, kayaks, and paddleboards. However, large riverine pools that may hold congregations of salmon can also be very popular with swimmers and even bathers (with use of human cleansers), particularly when the water is shallower and warmer, thus possibly creating scenarios where human disturbance and thermal stress events coincide. Both adult and juvenile Atlantic salmon are known to congregate into some relatively narrow cooler river area when water temperature approaches the thermal tolerance limit of salmon in the mainstream (Breau et al. 2007, Frechette et al. 2018). It is conceivable that regular human disturbance could push fish away from thermal refugia into warmer waters, with negative metabolic impacts if they are not able to locate other cool refugia and are forced to remain in warmer sites where oxygen is both more spare and consumed more quickly.

3.5 Introduction or Transmission of Pathogens and Invasive Species via Recreational Activities

Aquatic pathogens and diseases may be introduced to novel areas through the transport of infected or contaminated organisms and materials between isolated water bodies. How great a risk such introductions pose to a given fish species depends on a number of factors, including the extent of host specificity (i.e., the range of species a pathogen is capable of infecting), how successfully the pathogen can infect and spread in the new environment, and the host fish's resistance (ability to ward off infection) and resilience (capacity to persist and recover after infection). The duration of, and conditions during, the transfer period between water bodies is likewise important, as some species may withstand air exposure and suboptimal transfer conditions for extended periods of time. Although there is research on the spread of diseases affecting Atlantic salmon and other salmonids as a result of aquaculture (e.g., sea lice from salmon farms; McVicar 1997; Krkošek 2010), non-recreational contexts lie outside the scope of this work and we focus on identifying examples in the literature of pathogens and invasive species that may be transmitted by non-angling recreational activities. Dreissenid mussels, including Zebra mussels (*Dreissena polymorpha*) and quagga mussels (*D. bugensis*), have long been spreading across Canada and altering ecosystem structure and trophic dynamics in colonised areas (Karatayev et al. 2015), and can survive out of water for up to 5 days (Ricciardi et al. 1995), providing ample time for further spread via uncleaned equipment. While no investigations appear to have been published to date on Dreissenid mussels and riverine spawning habitat for Atlantic salmon, these mussels can have deleterious effects on the spawning behaviour and reproductive success of lake trout (*Salvelinus namaycush*) when potential spawning habitat is covered with mussels (Marsden and Chotkowski 2001). *Didymosphenia geminata*, also known as didymo, is considered an invasive or nuisance species of algae that creates extensive mucus-like mats along the beds of rivers and streams (Beville et al. 2012).

Didymo has high transferability via angling gear associated with salmonid fishing such as waders and other surfaces where the mucus-like alga can easily adhere (Beville et al. 2012). However, the potential impacts (if any) that didymo blooms have on Atlantic salmon are likely to be indirect (e.g., altering food webs for juvenile salmon that drift feed) rather than direct impacts such as modification of suitable spawning habitat for Atlantic salmon (Gillis and Chalifour 2010). For instance, this alga has been linked to changes in the invertebrates community of the Bonaventure River (Québec, CA), which could possibly alter food resources for salmonid species (Desmeules 2007). Given the lack of synchronicity between the former's blooming and the latter's spawning seasons and known examples of rivers hosting historically healthy salmon and didymo populations (Lindstrøm and Skulberg 2008), more research is required to assess whether didymo blooms pose genuine threats to salmon. On the other hand, results from Gillis (2018) nevertheless suggest it is probably not the case. Other invasive species may yet be identified as potential threats if anglers, boaters, and others engaging in aquatic recreational activities can serve as viable vectors. For example, the aquatic plant *Juncus bulbosus* has been observed to grow on salmon spawning grounds, leading to restricted flows, higher sediment accumulation, and ultimately the elimination of spawning habitat until the plant has been removed and loose gravel substrate restored (Velle et al. 2022).

The intentional, illegal release of live fishes by lone anglers for future angling opportunities is another potential route of invasive species introductions. Introduced predators can negatively affect native fishes, including juvenile salmonids, through elevated predation pressure (Valois et al. 2009; Bourret and Clancy 2018). The transfer and release of live baitfish is another concern that could be at least partially addressed by outreach and more stringent inspections of baitfish sold in tackle shops, where water may contain a number of potentially viable/transmissible pathogens (Mahon et al. 2018) and where there are greater chances of selling mislabelled and/or misidentified fish species and/or fishes carrying pathogens (e.g., Viral haemorrhagic septicaemia virus [VHSV]) that can spread further when released live into novel environments (McEachran et al. 2021a, 2021b). Bait fishing for Atlantic salmon is not legal in any North American jurisdiction of which we are aware, however bait fish may be introduced to waters with native Atlantic salmon populations.

Many microbial pathogens can survive for long transfer periods, are invisible to the naked eye, and are therefore more likely to spread unnoticed via contaminated gear. Salmonid anglers are often particularly mobile and at higher risk of transferring invasive species and pathogens than other anglers, travelling to and from various water bodies and not always properly cleaning and drying their equipment between trips (Anderson et al. 2014). Some pathogens (e.g., VHSV, a broadly infectious virus for many fish species, and infectious haematopoietic necrosis virus [IHNV], which is more specific to salmonids; Traxler et al. 1993) can remain viable on land for weeks (Anderson et al. 2014) and may pose risks to wild Atlantic salmon upon introduction by anglers, canoers, or other persons engaged in recreational activities involving the movement of equipment between isolated water bodies. This concern is not new, as anglers and recreation have previously been labelled as relatively higher risk than other potential dispersal vectors such as natural dispersal events in other assessments of species/pathogen introductions affecting salmonids (e.g., Arsan and Bartholomew 2008, 2009). It is unclear which pathogens are most likely to be introduced and cause harm to Atlantic salmon. For instance, VHSV is transmissible via gear used in recreational activities and may be more likely to be introduced, however Atlantic salmon are relatively but not entirely resistant to infection and mortality compared to other fishes that may occur in the same system (Kim and Faisal 2010;

Faisal et al. 2012). Whirling disease, a salmonid disease caused by infection with the parasite *Myxobolus cerebralis*, is highly transmissible in salmonids and Atlantic salmon are believed to be relatively susceptible to infection (though not as much as many *Oncorhynchus* spp.; Sarker et al. 2015). The parasite *Gyrodactylus salaris* was transported from Baltic salmon populations to Atlantic salmon rivers in Norway in or shortly before 1975 through supplementation stocking with catastrophic consequences for the infected populations (Johnsen and Jensen 1986; Sandodden et al. 2018). As of 2023, more than forty salmon rivers have been sterilised to eradicate the parasite and the salmon population was rebuilt at immense cost to avoid further spread. *Gyrodactylus* highlights the worst-case scenario of invasive species transmission in rivers in Canada but emphasizes that transfer of pathogenic or parasitic species on angling gear can potentially carry the highest risk among any activity on this list. With globalization and specialization of many Atlantic salmon anglers on this species, movement between Europe and Canada to target salmon is not at all unlikely and carries high risk of pathogen transmission.

To minimise the risks of invasive species and pathogen transfer, equipment (angling gear, canoes, etc.) should be dried and cleaned between uses on separate water bodies. Broadly speaking, outreach and education on contamination prevention (e.g., high-pressure washing boats, identifying and reporting disease outbreaks to relevant authorities; Rothlisberger et al. 2010; Wastesicoot 2018) might prove useful in mitigating the chances of invasive species and pathogen introductions through recreational activities (for an example see, Nature Conservancy of Canada 2018). In Iceland, all arriving passengers must disinfect their equipment before clearing customs and in Norway anglers are required to disinfect gear when moving between rivers to stop the spread of any pathogenic species. Requiring that fishing gear, boats, and other gear be cleaned and prohibiting the movement of uncleaned gear across isolated systems may be worthwhile gestures towards conservation efforts as well, however fully enforcing such restrictions to the maximum extent would likely be highly challenging due to the inability to fully monitor human movements across large spatial and temporal scales. Inspecting equipment to verify adequate decontamination is likewise unachievable for invisible pathogens, however it may be possible to detect macroscopic organisms that could pose threats to salmon or salmon habitat integrity (Rothlisberger et al. 2010).

4. Relevant Insight from Other Impacts of Non-Angling Recreational Activities/Stressors on Non-Salmonids

4.1 Underwater Flash Photography

The effects of underwater flash photography are not frequently studied in fish and we found no evidence of this being studied in Atlantic salmon. Flash photograph itself does not appear to induce significant physiological stress or behavioural impairment in fish, though human presence and interactions associated with swimmers and divers engaging in activities like underwater photography may disturb and stress fish (Harasti and Gladstone 2013; Knopf et al. 2018; De Brauwer et al. 2019). Like broader tourism impacts, underwater photography tends to be investigated in fishes that are commonly subjected to tourism-related stresses such as those living in coral reefs, small freshwater pools and streams in lower latitudes, and other habitats overlapping with popular tourist destinations. Overall, fish-focused ecotourism is more commonly practised in marine rather than freshwater systems, though many of the threats posed by ecotourism (e.g., direct interactions between humans and fish, habitat destruction) are shared across a range of environments (Bessa et al. 2017).

4.2 Other Potential Human Impacts

Sound disturbances from activities such as swimming and canoeing/kayaking have not been investigated in Atlantic salmon, though the concept has appeared in media following public disputes between anglers and canoers (see The Free Library 2006). Paddling sounds did increase heart rate and cardiac output in largemouth bass (*Micropterus nigricans*), implying elevated metabolic burdens during exposure and recovery over a ~10-20 min period (Graham and Cooke 2008). In salmon occupying rivers and streams near canoe, kayak, or other paddling activity areas, prolonged noise disturbances from those activities could induce some degree of stress if heart rates and metabolic demands remain elevated for long periods of time. It is also reasonable to believe that loud music, for instance from portable radio near the shoreline or above water, can disturb salmon.

Other activities such as food provisioning have been studied in wild fish (mainly in marine and/or tropical environments; reviewed by Patroni et al. 2018). This did not appear as a concern in our literature search, as adult Atlantic salmon cease feeding upon migrating while parr are cryptic, skittish, and feed on aquatic insects. Attempts to feed wild salmon would therefore be very uneventful and unlikely to succeed.

5. Risk Assessment

Using the information derived from our literature review above and combined with our own expert knowledge of Atlantic salmon biology, we identify activity-specific threats and consider life-stage specific risk profiles for each of the aforementioned possible threats. To do so we use a traditional risk assessment framework. Risk can broadly be defined as the probability and severity of a hazardous event occurring (Burgman 2005). In the context of this report, such an event would consist of adverse impacts on Atlantic salmon that could impact fitness or the population size (depicted in Table 1). Characterising the risk that various recreational activities pose to Atlantic salmon can be used to aid managers in decision-making that ideally decreases the probability and impact of hazardous events that could occur. Indeed, such risk assessments are exceedingly common for issues related to the environment (e.g., hydropower impacts, Shaktawat and Vadhera 2021; fisheries interactions, Gallagher et al. 2012). Ideally, such a risk assessment is conducted as part of an environmental risk management cycle, which involves problem formulation, hazard assessment (conducted above and informed by literature review), risk analysis (this part of the paper), sensitivity analysis (quantitative data lacking), and monitoring (a useful next step to improve the evidence base). Risk analysis is a tool used by regulators and proponents to guide planning and decision-making to reduce or eliminate the probability and severity of hazards (Burgman 2005; Shaktawat and Vadhera 2021). Here, we focus on the risk analysis. We identify the likelihood of each threat being a risk and the associated magnitude of consequence, assess our confidence in that threat assessment (based largely on the volume and quality of evidence), and identify where additional research is needed to reduce uncertainty. For the purpose of this paper, we consider likelihood that negative consequences to Atlantic salmon occur to span rare (<5% likelihood), unlikely (5 to 10%), possible (11 to 25%), likely (26 to 75%) and almost certain (76 to 100%) categories. For magnitude, we considered impacts that ranged from insignificant (no measurable impact on fish or habitat), to minor (sublethal impacts and/or minor alterations in habitat, unlikely to impact population-level processes), moderate (sublethal impacts and/or alterations in habitat that could reduce population size by <5%), major (potential for population reductions that could reduce population size by 5 to 25%) and severe (potential for population reductions that could reduce population size by over 25% or otherwise lead to extirpation or extinction).

One consideration that must be remembered is that variation in factors such as laws and cultural practices across different jurisdictions can heavily influence the overall risk assessment. For example, the use of ATVs is very strictly regulated and the regulation is highly enforced in Norway, the UK, and France, but the regulation enforcement might remain insufficient in some parts of Canada, so the risk of ATV-caused spawning habitat destruction will vary according to land use practices and the degree of enforcement (or lack thereof). Habitat access and land or waterbody ownership, too, can vary and will likewise affect the risks of certain threats occurring when the probabilities (or even possibility) of such events hinges on different legal and societal contexts. This also has implications for the extent of law enforcement efforts (e.g., patrols). For instance, ATVs may only be driven over rivers and streams when they are frozen except for some specifically approved crossing areas in Nova Scotia (Nova Scotia Department of Natural Resources and Renewables 2008), yet a lack of available enforcement pressure means illegal riding may still be taking place (e.g., CBC News 2021). Our risk assessment is focused on the eastern Canadian context. The risk assessment could be easily refined for other regions. In fact, given how the biology of Atlantic salmon, river characteristics, and human use patters can vary even between adjacent watersheds, risk assessments may best be conducted at more local scales.

Our risk assessment revealed that the likelihood of a given threat occurring varied from rare to likely. Likelihood can vary on a contextual basis (e.g., among space and time) so what we might deem as a rare event today could become quite likely if not certain in the future if the behaviour of recreationists active on Atlantic salmon rivers was to change. The consequence (i.e., magnitude) of a given event varied from insignificant to major. The overall risk assessment is a product of the likelihood and consequence and ranged from low to high. The most common categorization was "medium" with relatively few instances of low or high. Our risk assessment for the impacts of the recreational activities discussed herein are summarised in Table 2.

The activity that was deemed to be the highest risk was use of ATVs and associated habitat impacts. Because ATVs can only traverse shallow waters, it was assumed that ATV activity would be limited to shallow areas typical of what would be used for spawning. Therefore, ATVs have the potential to crush fertilized eggs and newly-hatched offspring as well as mobilise fine sediments that could smother spawning habitats. The extent to which ATV activity is an issue for a particular river will vary based on local regulations, accessibility, and the culture of recreationists. Although there is no literature specific to ATV impacts on Atlantic salmon, such impacts are generally well understood across benthic spawning fish (especially salmonids) with regulations in some jurisdictions that prohibit stream crossing (either year-round or seasonally) to protect fish habitat. Thus, although the literature base specific to Atlantic salmon is small, there is strong confidence that such impacts would be serious in streams and rivers that are small enough to permit motorised vehicle crossing. Wading by anglers (or others) and mountain bikes in areas where Atlantic salmon spawn could be damaging but in contrast to ATVs the consequences would be minor.

The activities that were deemed to be of lowest overall risk were underwater flash photography and food provisioning. Flash photography and food provisioning were deemed to be uncommon (rare) activities. Moreover, the consequence was considered insignificant based on literature and expert assessment (i.e., the co-authors). Flash photography would imply that imagery was being collected in low light conditions which although not impossible, is not needed given that Atlantic salmon (or other aquatic organisms or habitats) can be photographed more easily during the day (unless one is deliberately trying to obtain nighttime images). Flash photography has been investigated for reef fish (e.g., Heyman et al. 2010) but not Atlantic salmon. Food provisioning for Atlantic salmon is presumably very uncommon, not to mention that active feeding is somewhat limited and focused on natural food items rather than foods typically used in a provisioning context. Most of the literature on food provisioning of fish is specific to marine systems where predatory fish (usually sharks) are attracted to sites for tourism (e.g., Brunnschweiler et al. 2014). We are unaware of any food provisioning studies on Atlantic salmon.

The most common outcome of the risk assessment was "medium", although it is worth noting that based on our expert perspective the risks tend to be on the milder side of "medium" and are driven largely by the fact that most of the activities were quite likely to occur but only yield insignificant or minor consequences (in the threat matrix, most events were possible or likely to occur but of insignificant or minor consequence). Thus, despite the number of threats that could arguably be deemed to be moderate, from a practical perspective it is unlikely that any of these threats are constraining Atlantic salmon populations or leading to biologically meaningful impacts on Atlantic salmon habitat.

Disturbance arising from swimming, snorkelling, canoeing, kayaking, or rafting has been poorly studied for Atlantic salmon. Yet at least in Canada, these activities are quite common in river reaches where pre-spawn adult salmon will hold (e.g., Desmeules 2007; Beauchesne 2016; Gagné 2019; Bilodeau 2022; Langlois 2023). Limited research on other species reveals some evidence of short-term disturbances arising from such activities (Graham and Cooke 2008). Flow releases on regulated rivers is sometimes done in a way that creates recreational opportunities for kayaking and white-water rafting. Or, structures and other habitat alterations are made for recreational river users that can impact the flow and dynamics of the system (e.g., Murphy and Pearce 1985; Fox et al. 2016). Although flow regulation as a result of those specific recreational activities has not been studied for Atlantic salmon, it is well known that fish respond in diverse ways to flow variability. Depending on the rate and magnitude of flow changes for or associated with recreational river use (e.g., Carolli et al. 2017), negative impacts are possible. Given that high levels of these recreational activities can occur in some systems and at certain times, there is the possibility for behavioural alterations (e.g., temporary pauses in migration, need to select different habitats, potential for fallback) but that would require empirical research. Given how common these activities are and the perception that these activities may disrupt or disturb fish, this would be a high priority topic for study. We do note that swimming/snorkelling is a common tool used in fisheries assessment for Atlantic salmon and has been well-validated as a field method. Nonetheless, the level of effort (i.e., swimmers in a river) for Atlantic salmon stock assessment would presumably be quite minor compared to a site where there was easy recreational access and high levels of recreational swimming or canoeing, kayaking, or rafting activity. Local characteristics such as availability of deep pools and reaches without swimming activity/watercraft use would presumably also represent important modifiers of the effects of these recreational activities on Atlantic salmon.

There has been growing interest in the use of various chemicals on human skin and their potential to cause harm to aquatic life. In particular, sunscreen products have been identified as being damaging to corals. There is no research specific to Atlantic salmon and sunscreen (or other cosmetics, or even insect repellents). Given the large volume of water in most rivers it is unlikely that these products are having detrimental impacts on fish. Nonetheless, targeted research in a laboratory environment to understand potential impacts on Atlantic salmon as well as efforts to quantify the concentrations and fate of such products in Atlantic salmon rivers could be a useful research activity.

Litter of any sort is unsightly but is unlikely to represent any biologically relevant threat to Atlantic salmon. Litter can arise from lost fishing gear or other recreationists improperly disposing of food wrappers, beverage containers, etc. Although there has been much attention focused on microplastics of late it is unlikely that recreational activities would be a major source. Efforts to encourage river users to put trash where it belongs could help to reduce the presence of such litter in Atlantic salmon waters. Given that adult Atlantic salmon may continue to feed during their upriver migration, there is certainly potential for ingestion of some artificial materials (e.g., lead, plastics) associated with some fishing flies or lures.

Several activities have the potential to introduce invasive species/pathogens to waters. Indeed, these effects are ubiquitous today given the manifold role of humans as vectors for invasive species. Wherever humans and nature intersect, effects could occur, and this is certainly the case for Atlantic salmon rivers. Swimmers are unlikely to be a major source, but unclean wetsuits, waders, or watercraft could all potentially lead to the introduction of invasives – from algae to pathogens. However, this issue is germane to any system where recreationists are active on aquatic systems. The direct release of introduced fish (e.g., baitfish and gamefish) would represent a rather serious threat to any aquatic system with such impacts dependent upon propagule pressure and the life history of the invader, among other factors. The threat to Atlantic salmon does not seem to be any more heightened or dire relative to biota in other aquatic systems. Efforts to educate river users about invasive species and the adoption of mitigation activities (e.g., cleaning gear between uses at different sites) is the most prudent approach for ensuring aquatic systems are protected from the unintentional introduction of invasives.

The life-stage specific risk assessment (Table 3) emphasizes how risk is not ubiquitous for a given activity across life stages. This is in part because of the different sensitivity of various life stages to stressors but also reflects the fact that some recreational activities are unlikely to occur in areas where certain life stages reside. What is notable is that the early life stages appear to have somewhat greater risk albeit this is dependent upon threats and contexts.

6. Conclusions

The literature base specific to Atlantic salmon and the effects of various recreational activities was relatively small. Indeed, even when conducting a more global review and drawing in literature on diverse species from around the globe, most of the recreational activities of interest in this report have been poorly studied. Why? In short, relative to the other threats facing fish (including Atlantic salmon; see Mills 1986; Forseth et al. 2017; Smialek et al. 2021; Thorstad et al. 2021), these impacts have presumably been deemed to be relatively minor. That is often the case for non-extractive recreational activities yet there are also a growing number of examples of where superficially benign activities (e.g., bird watching, hiking) can have negative impacts on wildlife (Boyle and Samson 1985). A common feature of these studies whether in terrestrial or aquatic systems is that impacts are context specific (Tablado and Jenni 2017). What may be a threat for one location, season, or life-stage may not be a threat for another combination of contexts. There is also potential for threshold responses where, for example, wading by one angler (which can crush developing offspring) may have negligible (unmeasurable) impact on recruitment yet if wading effort were to be high and focused on key spawning areas then the impact could be substantial. When conducting a risk assessment as we have done here, it is important to recognize that context can change over time as there are shifting patterns in human recreational activity (e.g., changes in the timing, location, and/or intensity/frequency of recreational activities; McKercher 1992; Thorp et al. 1997).

Risk assessments benefit conservation and management efforts by laying out various potential challenges and pitfalls in a comprehensive and transparent manner. Actionable recommendations can be made to inform guidelines and initiatives for identified risks with high likelihoods and/or high-magnitude consequences, while risks for which we have substantial knowledge gaps or greater degrees of uncertainty are also given due consideration and opportunities for further knowledge generation can be highlighted (Game et al. 2013). The biggest challenge with assessing the effects of non-extractive recreational activities on Atlantic salmon is that we had to draw upon a small evidence base and often make extrapolations or educated guesses (based on expert knowledge) when conducting the risk assessment. Clearly there are some research gaps but the relative profitability of those gaps and their ability to reduce uncertainty for the overall risk assessment is highly variable. Nonetheless, there are several empirical research studies that could be conducted to further understand the risk of recreational activities specific to Atlantic salmon as identified above (i.e., impacts of swimming/watercraft on the behaviour of adult Atlantic salmon; impacts of sunscreen products on juvenile and adult Atlantic salmon), but overall threats like salmon farming, habitat alteration (Forseth et al. 2017), river fragmentation (van Puijenbroek et al. 2019), and climate change (Jonsson and Jonsson 2009) seem to be more important when it comes to the future of Atlantic salmon populations. It is possible to quantitatively assess the relative impacts of different threats to Atlantic salmon (as has been done for terrestrial wildlife; see Naidoo and Burton 2020) which could be a useful next step to properly contextualise the impacts of non-extractive recreational activities on Atlantic salmon populations.

A transient, recreational stressor that might have little effect on salmon in colder waters might become disproportionately deleterious at higher temperatures as waters warm from unmitigated climate change. In systems where Atlantic salmon face multiple stressors (which is likely the norm) non-extractive recreational activities could contribute to the cumulative stress experienced by fish (e.g., contribute to overall allostatic load; Romero et al. 2009; Edes et al. 2018) and could interact with other stressors like climate change in synergistic ways (Folt et al. 1999). For example, while warmer waters alone are more stressful to salmon, warming may also increase the amount and types of pressures on salmon stemming from recreational activities which may lead to greater effects than those observed today. Thus, failure to address the serious large-scale threats such as climate change or hydropower development will mean there could be little ultimate purpose in addressing the smaller-scale recreational impacts that we reviewed here.

So, what is the overall likelihood that non-extractive recreational activities impact Atlantic salmon in eastern Canada? Quite likely. However, the magnitude of that impact is presumably quite low aside from unique instances when human activities (with high effort) intersect with vulnerable life stages/habitats. It is therefore crucial to have good data on populations to identify rivers where there may be undue harm caused by recreational activity due to a small spawning population or limited suitable spawning grounds. Likewise, data on the prevalence and timing of higher-risk recreational activities (e.g., ATV driving) in those areas would also be a benefit for management efforts. We are unaware of a single study that draws a link between any of the non-extractive recreational activities explored here and the decline of an Atlantic salmon population. However, for populations that are already imperilled it is conceivable that such activities could compound existing issues and could prevent the recovery of populations, particularly where spawning areas are affected by activities. Indeed, returning adults are relatively resilient to disturbances such as recreational fishing that has direct physical and physiological assault, whereas juveniles and eggs are likely less resilient and therefore less tolerant of stress caused by recreational activities. On the other hand, the potential population impacts of egg loss may be less than those associated with the death of mature adults given the former's propensity to naturally high mortality rates. Additional empirical research specific to Atlantic salmon would be needed to reduce uncertainty and address this knowledge gap. In rivers with high levels of swimming or other human presence in/on the water, there is a need to understand how the presence of humans impacts the migration biology of adult Atlantic salmon en route to spawning grounds (or holding prior to spawning). Moreover, investigating activities that overlap with spawning and rearing areas such as ATVing, wading, and biking, and understanding how these impacts could interface with synergistic stressors such as poor marine survival or infection pressure from diseases to have population-scale consequences is also important. The framework that we developed here could easily be applied to other regions or contexts where Atlantic salmon rivers are present.

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Data Statement

There are no data reported.

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Boxes, and Tables

Box 1. List of recreational activities considered in our literature searches and screening. *For angling, the effects of catch-and-release angling were not considered, but indirect impacts (e.g., presence of lost or discarded lures) were considered relevant for our review.

Swimming	Tourism/ecotourism
Diving	Wading
Snorkelling	Angling*
SCUBA	Rafting
Canoeing	Use of other non-motorised watercraft
Kayaking	ATV/amphibious vehicle use

Table 1. Schematic of the relationships between risk likelihood and consequence (in an eastern Canadian context) with respect to overall risk assessment calculation. The assessment is somewhat subjective by nature but consequence magnitude ranges from "insignificant" (impacts are likely to not lead to meaningful decreases in fitness or population size) to "severe" (impacts would potentially yield extinction of a population). For likelihood, "almost certain" would mean expectation that a consequence would be expected while "rare" would suggest that likelihood is extremely unlikely. See text for specific details on thresholds used.

		Magnitude of Consequence				
		Insignificant	Minor	Moderate	Major	Severe
Likelihood of Threat	Almost certain	**Medium**	**High**	**High**	**Extreme**	**Extreme**
	Likely	**Medium**	**Medium**	**High**	**Extreme**	**Extreme**
	Possible	**Low**	**Medium**	**Medium**	**High**	**Extreme**
	Unlikely	**Low**	**Low**	**Medium**	**High**	**High**
	Rare	**Low**	**Low**	**Low**	**Medium**	**High**

Table 2. Summary of the risk assessment and quality of the available evidence base pertaining to the effects of individual non-angling recreational activities and their corresponding threats on Atlantic salmon in Canadian riverine systems.

Possible Threat		Likelihood	Consequence	Overall Risk	Evidence Base
Alterations to Habitat	Wading	Likely	Minor	Medium	Moderate
	ATVs	Possible	Major	High	Moderate
	Horseback riding	Unlikely	Minor	Low	Weak
	Mountain bikes	Possible	Minor	Medium	Weak
	Flow alteration for recreation (e.g., rafting)	Possible	Moderate	Medium	Moderate
Pollution and Toxicological Effects	Litter (e.g., lost fishing gear)	Unlikely	Minor	Low	Weak
	Sunscreen/cosmetics	Likely	Insignificant	Medium	Weak
Disturbances to Individual Fish	Swimming/snorkelling	Likely	Insignificant	Medium	Moderate
	Canoe/kayak/rafting	Likely	Insignificant	Medium	Weak
Pathogens and Invasive Species	Fishing gear	Likely	Moderate	Medium	Weak
	Release of live fishes	Likely	Moderate	Medium	Strong
	Canoe/kayak/rafting	Possible	Moderate	Medium	Weak
Other Impacts	Underwater flash photography	Rare	Insignificant	Low	Weak
	Food Provisioning	Rare	Insignificant	Low	Weak

Table 3. Summary of the life-stage specific risk profiles and their corresponding threats for Atlantic salmon in riverine systems.

Possible Threat		Risk to...				
		Fertilized Eggs	Early Life Stages	Smolts	Pre-Spawn Adults	Spawning Adults
Alterations to Habitat	Wading	Medium	Medium	Low	Low	Low
	ATVs	Extreme	Extreme	Low	Low	Medium
	Horseback riding	Medium	Medium	Low	Low	Medium
	Mountain bikes	Medium	Medium	Low	Low	Medium
	Flow alteration for recreation	Medium	Medium	Low	Low	Low
Pollution and Toxicological Effects	Litter (e.g., lost fishing gear)	Low	Low	Low	Low	Low
	Sunscreen/cosmetics	Low	Low	Medium	Medium	Low
Disturbances to Individual Fish	Swimming/snorkelling	Low	Low	Low	Medium	Medium
	Canoe/kayak/rafting	Low	Low	Low	Low	Medium
Pathogens and Invasive Species	Fishing gear	High	High	Low	Low	Medium
	Release of live fishes	High	High	High	Low	Low
	Canoe/kayak/rafting	High	High	High	Medium	Medium
Other Impacts	Underwater flash photography	Low	Low	Low	Low	Low
	Food provisioning	Low	Low	Low	Low	Low