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Loch Ness © Olivia M. Simmons

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Abstract

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The demand for hydropower production is rising as the world transitions towards renewable energies. As such, many new hydropower projects are being planned. In Loch Ness, Scotland, plans for two new pumped storage hydropower (PSH) schemes are under development, which both intend to use the loch as their lower reservoirs. The Ness District Salmon Fishery Board has expressed concern over the potential impacts these new PSH projects may have on the Atlantic salmon population in the Loch Ness Catchment and the broader ecology of the loch. The Atlantic salmon population in this system is already under pressure from several factors, including other already developed hydropower schemes, barriers to their migration such as dams and weirs, exploitation from fisheries, aquaculture, and more. Thus, the objective of this report is to provide a review of the ways PSH schemes can affect the environment, followed by a discussion of how the proposed projects in Loch Ness might affect the salmon population (including some of the knowledge gaps about these effects). Then we provide suggestions for studies to address the identified knowledge gaps and propose some mitigation and offsetting measures to help the Atlantic salmon in Loch Ness. Overall, we found a lack of knowledge about how Atlantic salmon migrate through the loch, which is imperative for understanding how closely they will encounter the proposed projects. We also found a lack of knowledge about how the new PSH schemes might impact the flow patterns and temperature regimes in Loch Ness, which will have implications for migrating salmonids and the broader aquatic community in the loch. We recommend that further research is required to better understand these critical matters.

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Summary for management

One of the goals of this report was to review the environmental impact assessment for the proposed Red John Pumped Storage Hydro (PSH) scheme and the environmental scoping report for the proposed Loch Kemp PSH scheme to identify knowledge gaps related to possible impacts of these schemes on Atlantic salmon and the broader ecological community in Loch Ness. With the knowledge gaps in mind, we then recommended some future studies and provided some advice for mitigating and offsetting the potential effects of the proposed schemes on Atlantic salmon. We note the importance of evaluating the effects of the proposed PSH scheme together with the effects of the current Foyers scheme that operates in Loch Ness, as the impacts of the three schemes operating simultaneously are likely to be cumulative. Here, we provide a brief synopsis of those findings.

Knowledge gaps

1. It is not known how, and to what extent, the proposed PSH schemes will alter the natural flow patterns in Loch Ness. Flow is an important navigational cue for migrating Atlantic salmon.
2. There have not been any published studies detailing the spatial distribution of smolts as they migrate through Loch Ness. This is important to know to evaluate the extent that migrating smolts will encounter the PSH schemes.
3. There is currently one PSH scheme in operation at Foyers on Loch Ness. It has been in operation since 1974, yet it is unknown how this scheme currently affects Atlantic salmon in the loch.
4. It is unknown how all the PSH schemes will affect the temperature profile and thermocline in Loch Ness.
5. It is unknown how changes to the natural flow patterns and temperature regimes in the Loch caused by the PSH schemes will be further affected by climate change.
6. There has been no consideration of whether either of the proposed PSH schemes will result in gas supersaturation in Loch Ness.

Recommendations for future studies

1. Hydraulic modelling of Loch Ness to understand how the flow patterns will change.
2. Tracking studies of smolts and adult Atlantic salmon to predict the extent to which they will encounter the PSH schemes.
3. Modelling the effect of operating the schemes on the temperature regime and thermocline in Loch Ness.
4. Studying whether gas supersaturation in Loch Ness will result from operating the PSH schemes.
5. Long-term monitoring of the site to chronicle how the environment changes.

Mitigative and offsetting measures

1. Mitigate negative effects by adjusting PSH operation schedules to account for smolt and adult Atlantic salmon migration periods.
2. Offset negative effects by helping smolts successfully navigate through other parts of the catchment by blocking smolt passage out of Loch Oich via the Caledonian Canal.
3. Offset negative effects by making improvements to current fish passage structures at barriers throughout the catchment.
4. Offset negative effects by removing unnecessary barriers to Atlantic salmon migration throughout the catchment.

Contents

Foreword

This report was commissioned by the Ness District Salmon Fishery Board to review the possible environmental effects of two proposed pumped storage hydropower schemes in Loch Ness, Scotland. Loch Ness forms a part of the migratory route for Atlantic salmon in the Ness Catchment, so the effects of the proposed projects on these fish were of particular interest. In June 2023, we conducted a site visit to the Loch Ness catchment to observe the proposed locations for the new pumped storage hydropower schemes and to better understand the current factors that could be contributing to the decline in Atlantic salmon production in the area. This site visit informed the work to produce this report, which includes a general overview of the environmental effects of pumped storage hydropower schemes, a more detailed account of how the proposed schemes in Loch Ness may impact the loch's ecology and migratory salmon population, and some important knowledge gaps and potential mitigation measures that can be undertaken to protect the salmon population.

We thank our contact person at the Ness District Salmon Fishery Board, Brian Shaw, for sharing invaluable information for this report during the site visit and for good cooperation during the writing of the report.

Trondheim, Norway, August 2023

Olivia M. Simmons

1 Introduction

Loch Ness, famous for its mythological lacustrine monster, is an area of cultural and ecological importance in Scotland. The loch is home to a variety of aquatic species, and the wider Ness Catchment is home to important and protected aquatic species, such as freshwater pearl mussels (*Margaritifera margaritifera*) and Atlantic salmon (*Salmon salar*) (Maitland 1981; Addy et al. 2012). Currently, there is a pumped storage hydropower scheme (PSH) located at Foyers, which uses Loch Ness as its lower reservoir. However, two more PSH are now in development, both of which intend to use Loch Ness as a lower reservoir. The Red John Pumped Hydro Scheme, the first development, has been granted planning permission, though construction is yet to start. The second, known as the Loch Kemp Pumped Hydro Storage Scheme, has not received planning permission (**Figure 1**). Currently, there is little known about how these new PSH projects will affect the ecology of Loch Ness. To date, there has been an environmental impact assessment published for the Red John Pumped Hydro Scheme and an environmental scoping report for the Loch Kemp Pumped Hydro Storage Scheme, both of which will be reviewed in this report.

The purpose of this report is to provide information about the possible ecological effects of PSH, with an emphasis on Atlantic salmon, identify some potential impacts of the proposed projects in Loch Ness on Atlantic salmon, identify knowledge gaps related to the development of these projects, and suggest measures to mitigate or offset the environmental impacts of the proposed projects.

1.1 Loch Ness and the Ness Catchment

Loch Ness is a large, elongated, oligotrophic lake in the highlands of Scotland. With a volume of approximately 74.52 x 10^8 m^3, it has more water than any other lake in Scotland. It is located southwest from Inverness, at an altitude of 15.8 m above sea level. It has a relatively simple bathymetry, comprising two basins, and a maximum and mean depth of 230 m and 132 m, respectively. The loch is 39 km long, has a mean width of 1.45 km, and a surface area of approximately 56.4 km^2. It has a narrow shoreline and steeply sloping banks. The water level in Loch Ness varies over time, with monthly variability of about 27 cm (Maitland 1981). The loch runs in a northeast/southwest direction, and forms nearly half of one of Scotland's most important waterways, the Caledonian Canal.

Several rivers flow into Loch Ness, including the Oich, Enrick, Moriston, Tarff, and Foyers. The River Oich drains into the southwestern end of Loch Ness, the rivers Moriston and Enrick are located on the northern side of Loch Ness, while the River Foyers is on the southern side. The River Moriston, with a mean monthly flow of 20 m^3s^{-1}, has been designated as a 'special area of conservation', due to the presence of freshwater pearl mussels (Addy et al. 2012; National River Flow Archive 2023a). It is also a valuable habitat for Atlantic salmon. The River Ness, which is separated from Loch Ness by the Ness weir and has a mean monthly flow of 90.8 m^3s^{-1} (National River Flow Archive 2023b), flows approximately 10 km from Loch Ness to the ocean and is the main natural passage for Atlantic salmon migrating to and from the sea (**Figure 1**).

Loch Ness is one of the lochs in the Great Glen, located on a geological fault line that bisects the Scottish Highlands. A series of three inland lochs run along the fault line and are connected by rivers and canals. From east to west, the River Ness and the Caledonian Canal connect Loch Ness to the Moray Firth, Loch Ness is connected to Loch Oich via the River Oich and the Caledonian Canal, Loch Oich is connected to Loch Lochy via the Caledonian Canal, and Loch Lochy drains into the sea loch Loch Linnhe via the River Lochy. The middle loch, Loch Oich, is also fed by the River Garry, an important river for Atlantic salmon (**Figure 1**).

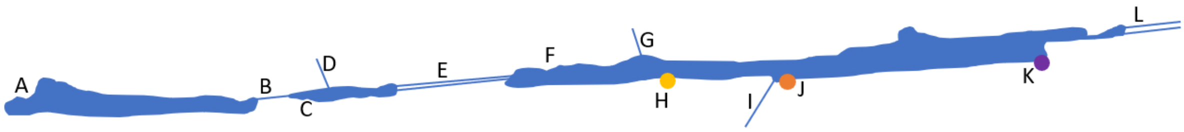

Figure 1. *An illustration of some of the water bodies and PSH schemes in the Ness Catchment, including Loch Lochy (A), the Caledonian Canal (B), Loch Oich (C), the River Garry (D), the Caledonian Canal and River Oich (E), Loch Ness (F), the River Moriston (G), the proposed Loch Kemp PSH scheme (H, in yellow), the River Foyers (I), the Foyers PSH scheme (J, in orange), the proposed Red John PSH scheme (K, in purple), and the Caledonian Canal and River Ness (L). The water bodies are in blue while the current and proposed PSH schemes are yellow, orange, and purple.*

1.2 Selected anthropogenic uses of Loch Ness

According to the Water Framework Directive, Loch Ness has good ecological status. Nonetheless, there are several ways humans use the loch, which may affect its ecology. The Foyers Power station includes a PSH scheme that uses Loch Ness as its lower reservoir and a conventional hydropower scheme. The PSH scheme has been in operation since 1974 and has a generating capacity of 300 MW. The conventional scheme at Foyers has a generating capacity of 5 MW. There are several other hydropower plants in the catchment, including the Glenmoriston power station (37 MW generating capacity) located on the River Moriston and the Glendoe hydroscheme (100 MW) fed by a reservoir in the upper reaches of the River Tarff (SSE 2023). Elsewhere in the catchment, there is an 18 MW hydropower scheme at Loch Quoich and a 20 MW hydropower scheme at Invergarry. The tailrace from Loch Quoich feeds into Loch Garry and the Invergarry scheme feeds into the River Garry (SSE 2023). Together, these hydropower schemes use up to 56% of the runoff in the catchment, which can cause abrupt changes in the flow downstream in the River Ness (National River Flow Archive 2023b).

There are several human-made barriers in the waterways draining into and out of Loch Ness. For example, on the River Moriston, which flows into Loch Ness, there are two barriers of note. Firstly, the Dundreggan Dam, which provides storage for the Glenmoriston hydropower station, is a large dam with two radial gates, a central drum gate, and a Borland fish pass for migrating fish (Historic Environment Scotland 2023). In the upper River Moriston, the Ceannacroc Heck dam was installed with a fish trap in the 20th Century. Though the trap is no longer used, the dam is still in place. The dam has a fish ladder, though it is unclear whether the ladder's design is optimal for both the upstream and downstream passage of migrating fish. Another example of a human-made barrier in rivers draining into Loch Ness is the Aberchalder Weir, which separates Loch Oich from River Oich. This weir consists of a raised embankment with a paved slope. There is a gap at the south end of the weir. There is also another noteworthy barrier, the Ness Weir, which divides the River Ness from Loch Ness (**Figure 2**).

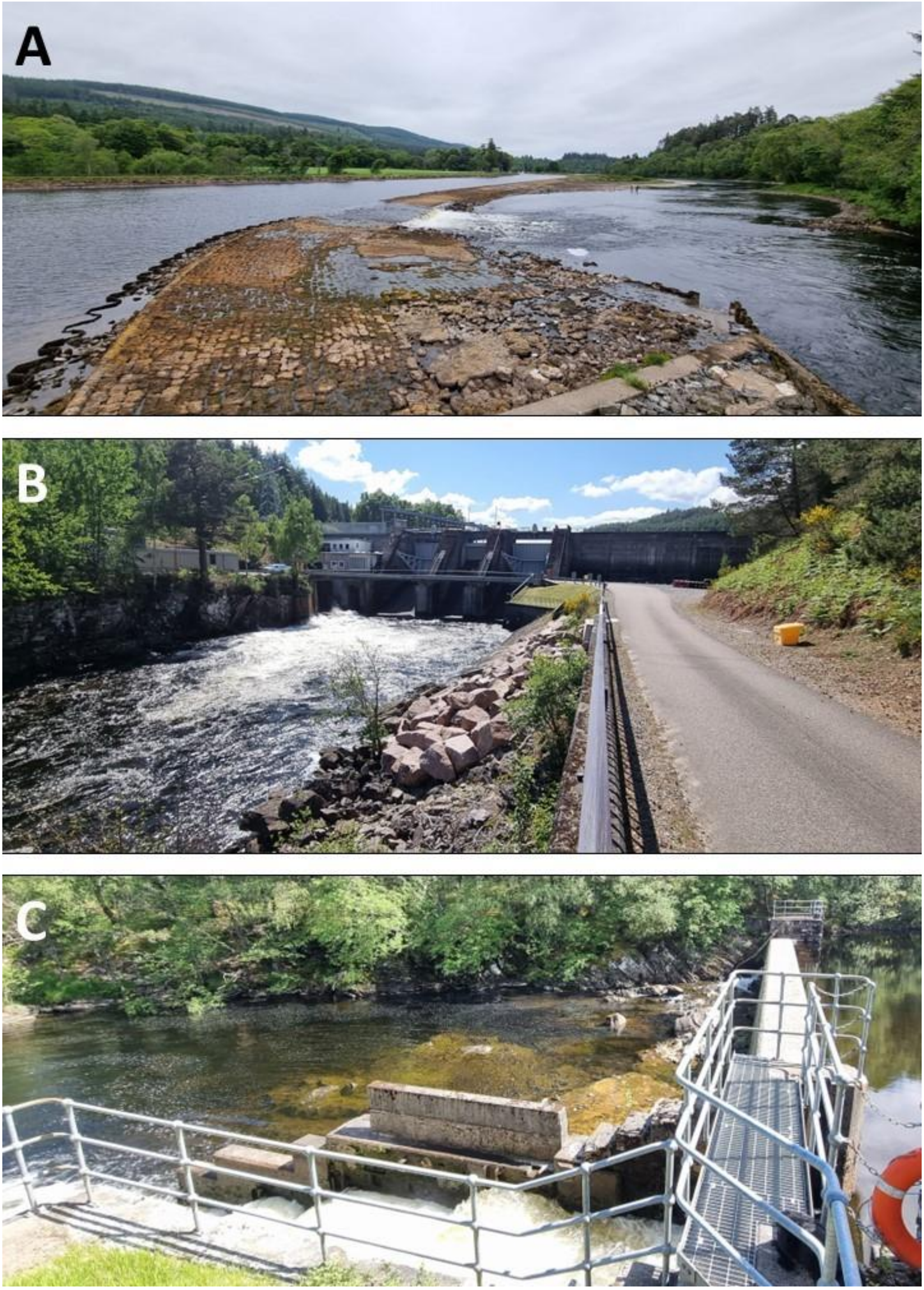

Figure 2. *The Ness Weir (A), Dundreggan Dam (B), and Ceannacroc Heck Dam (C). Photos from Anders Foldvik.*

Atlantic salmon are caught by recreational anglers throughout the Ness Catchment. Since 1994, an increasing proportion of anglers employ catch and release. There was also, historically, a netting fishery for Atlantic salmon in the catchment. However, there were no salmon caught this way from 2013-2021 (Brian Shaw, Personal Communication). In addition to recreational fisheries and commercial netting, Mowi Scotland Ltd. operates several juvenile Atlantic salmon farms in the Ness catchment, including Loch Ness, where there are 18 freshwater cages, and Loch Garry, with 22 freshwater cages. Though technically outside the Ness Catchment, Loch Lochy, which is artificially connected to Loch Oich in the Ness Catchment via the Caledonian Canal, also has a Mowi Scotland Ltd. Atlantic salmon farm with 36 freshwater cages (Natural Scotland 2023).

Finally, the Caledonian Canal, first opened in 1822, crosses the Scottish Highlands to provide a route for boats to sail from one coast to the other. It has a total length of approximately 97 km, of which 61 km is comprised of lochs Ness, Oich, and Lochy. The canal contains 29 locks, 10 bridges, and 42 pairs of gates (Cameron 2017). It is a popular travel route with substantial boat traffic. For example, in 2018 there were approximately 1 200 transits from coast to coast and 65 000 movements of boats within the canal (Scottish Canals 2020). The stretch of the Caledonian Canal between Loch Ness and the Moray Firth contains a smolt bywash (**Figure 3**), though the effectiveness of the bywash is unclear.

Figure 3. *Pictures of the Caledonian Canal showing one of the locks (A) in Fort Augustus and another lock by the smolt bywash between the canal and the River Ness (B). Photos from Anders Foldvik.*

1.3 Ecology of Loch Ness

Loch Ness is a seasonally stratified monomictic lake, which means that mixing between the stratified layers of water in the lake occur once a year (Smith et al. 1981; Wetzel 2001). The thermocline typically begins to develop in June at a depth of approximately 30 m (George and Winfield 2000). The loch is oligotrophic, and the water is stained reddish-brown due to the high concentrations of humic material in the catchment (Bailey-Watts and Duncan 1981a). Due to the high colouration of the water, light can only penetrate approximately the top 10 m of the water column (George and Winfield 2000). Thus, the phytoplankton biomass in Loch Ness is relatively low (Bailey-Watts and Duncan 1981b). The loch hosts a zooplankton community mainly comprised of copepods (Maitland, Smith, and Dennis 1981). Both phyto- and zooplankton are mostly found in the top 20-30 m of the loch (George and Winfield 2000). Several species of fish are present in the loch, including Arctic charr (*Salvelinus alpinus*), brown trout (*Salmo trutta*), northern pike (*Esox Lucius*), and three-spine stickleback (*Gasteroseus aculeatus*). There are three species of lamprey in Loch Ness: sea lamprey (*Petromyzon marinus*), river lamprey (*Lampetra fluviatilis*), and brook lamprey (*L. planeri*). Two salmonid species use the loch as a part of their migration route, namely Atlantic salmon (*Salmo salar*) and sea trout (i.e. anadromous brown trout, *S. trutta*) (Maitland, Smith, and Adair 1981). Like the loch's plankton community, the fish of Loch Ness tend to reside in the top 30 m of the water column and appear to be more densely found in the southern half of the loch (George and Winfield 2000). A more detailed account of the ecology of Loch Ness can be found in Maitland (1981).

1.4 Atlantic salmon and Loch Ness

Loch Ness forms a part of the migratory route for Atlantic salmon smolts migrating out of the catchment and returning adults. Data from the Ness District Salmon Fishery Board indicates a long-term decline in the numbers of adult salmon in the River Garry and more recent declines in the River Moriston (**Figure 4**). The Ness District Salmon Fishery Board's Fisheries Management Plan for 2021 to 2030 identifies several factors that could be contributing to the decline in Atlantic salmon production. These factors include exploitation from fisheries (both legal and illegal exploitation), predation, aquaculture, water quality and quantity, changes to aquatic thermal regimes, loss of habitat, and barriers during migration (Ness District Salmon Fisheries Board 2021). Outside Loch Ness, Atlantic salmon from the Ness catchment are known to be important prey for bottlenosed dolphins (*Tursiops truncatus*) in the Moray Firth (Janik 2000; Fernandez-Betelu et al. 2023), a popular tourist attraction (Moray Dolphins Guide 2023).

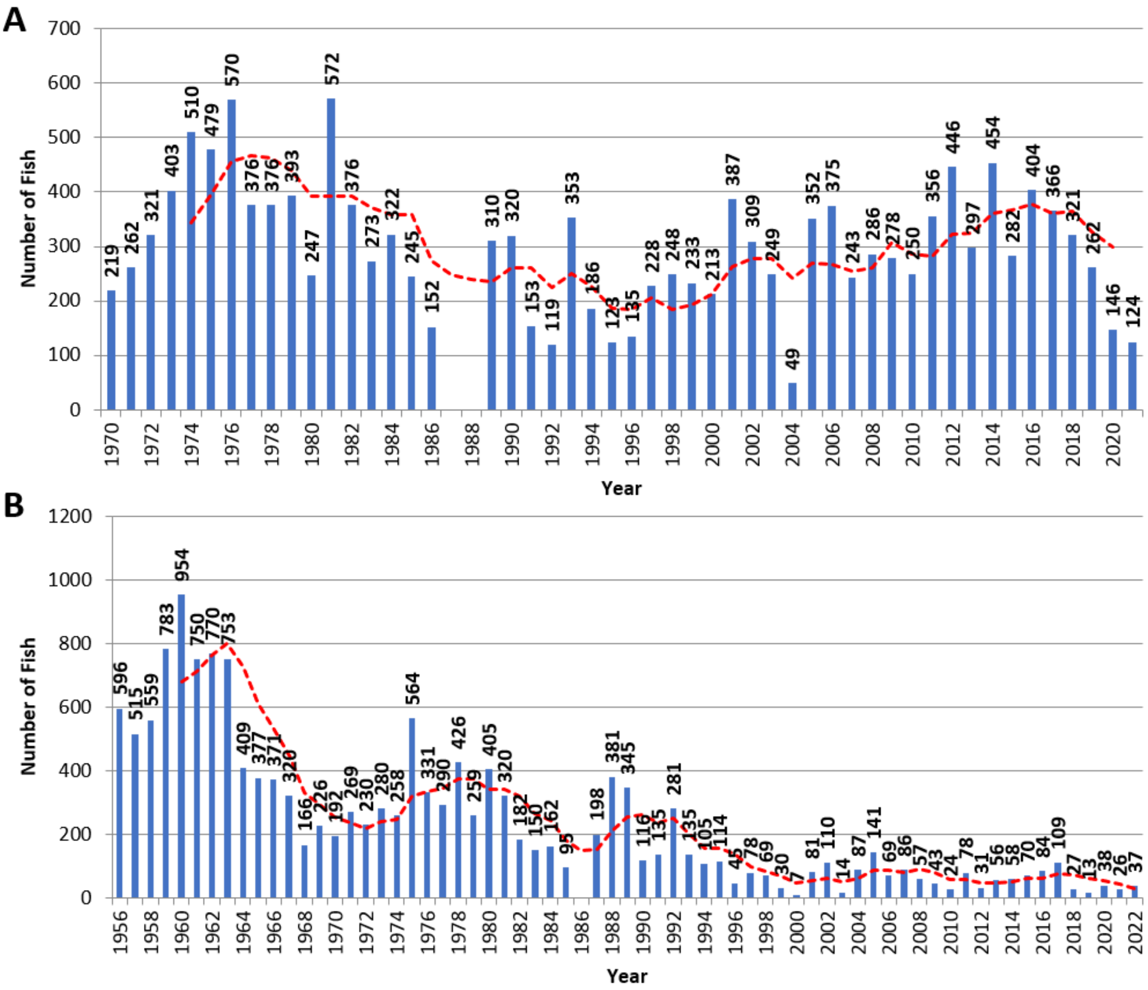

Figure 4. *The number of adult Atlantic salmon detected at fish counters on the River Moriston (A) and the River Garry (B). The blue bars and numbers above the bars are the counts for each year, while the dashed red line indicates the five-year mean count. The figures are provided by the Ness District Salmon Fishery Board while fish counter data presented in the figures is provided by Scottish and Southern Energy.*

To date, few scientific studies have focused directly on Atlantic salmon in the Ness Catchment. However, from 2019 to 2022, Atlantic salmon smolts, the migratory juvenile life stage of salmonid species, were tracked as they migrated down the River Garry and through lochs Oich and Ness as a part of the Moray Firth Tracking Project (Atlantic Salmon Trust 2022). When the smolts enter Loch Oich from River Garry, they can migrate eastwards via the River Oich or the Caledonian Canal to Loch Ness. From Loch Ness, they can continue east to the sea via the River Ness or the Caledonian Canal. However, if smolts head west in Loch Oich, they can exit via the Caledonian Canal and find themselves in Loch Lochy. A series of early reports (see below) from the project suggest that many Atlantic salmon smolts 'go missing' as they migrate to sea in this system.

From the early Moray Firth Tracking Project reports it is evident that few smolts make it from the River Garry to the furthest downstream tracking receiver in River Ness. Just 9%, 20%, and 19% of the tagged smolts were detected at the final River Ness receiver in 2019, 2021, and 2022 (Scottish Centre for Ecology and the Natural Environment 2019, Lothian 2021, Lothian 2022). There seems to be a problem for smolts attempting to exit Loch Oich, where the safest route is via the River Oich, which flows to Loch Ness. Nonetheless, smolts sometimes left Loch Oich via the Caledonian Canal at the eastern end of the loch, or the Caledonian Canal at the western end of the loch. In 2019 and 2021, half of the smolts that initially began to head west from Loch Oich turned around and returned east. Some of the smolts that went west were later detected in Loch

Locky (e.g. 4% of the smolts tagged in 2021) (Scottish Centre for Ecology and the Natural Environment 2019, Lothian 2021). In 2022, only 25% of the smolts detected heading west from Loch Oich turned around and went east. Furthermore, even smolts that initially move in the 'correct' easterly direction in Loch Oich can display confusion during navigation. This was observed in 2022, when two smolts that initially demonstrated easterly movements turned around to head west. One of these two smolts eventually turned around again, continuing to migrate eastwards. Even when smolts exited Loch Oich to the 'correct' direction in the east they could take different routes to Loch Ness (Lothian 2022). For example, in 2019 43% of the tagged smolts exited Loch Oich via River Oich and 13% exited via the Caledonian Canal. Nearly all the smolts that migrated down River Oich reached Loch Ness (40% of the tagged smolts) while just a single fish that migrated down the canal was detected in Loch Ness (1% of the tagged smolts). In the same year, only smolts that left Loch Ness via the River Ness made it to the Moray Firth, while no smolts leaving Loch Ness via the canal were detected again (Scottish Centre for Ecology and the Natural Environment 2019). This suggests that the Caledonian Canal not only causes directional confusion for the smolts migrating to sea but also contributes to the high mortality rate of the migrant fish.

1.5 Description of the proposed PSH projects

1.5.1 Basics of PSH

PSH operates as an energy storage technology by using the potential energy of water to store and release electricity. To do so, two connected reservoirs with different elevations are required. The reservoirs might be natural lakes, modified lakes, or human-made reservoirs. When energy demand is low, water is pumped via reversible turbines from the lower reservoir to the upper reservoir. When energy demand is high, the water is released to pass back through the turbines, producing electricity as it discharges. Though PSH schemes are a part of the clean energy transition, they can have adverse local impacts, several of which are reviewed in Section 2 (Pitorac et al. 2020; Normyle and Pittock 2020; Nikolaos et al. 2023).

1.5.2 Red John PSH scheme

The Red John PSH scheme has recently been granted planning permission. The scheme will have a capacity of 450 MW. It will be constructed approximately 14 km southwest of Inverness. The upper reservoir will have a total volume of 5 x 10^6 m^3, though 4.9 x 10^6 m^3 will be its working volume, and will be excavated from a hill above Loch Ness. The rock excavated from the upper reservoir, as well as from the construction of the waterway between the upper and lower reservoirs, will be used to build embankments around the upper reservoir. The inlet/outlet of the upper reservoir will be in a trench at the bottom of the reservoir and will have a coarse screen and gates. There will also be a spillway to remove excess water from the upper reservoir and a scour pipe located within the structure containing the inlet/outlet.

Loch Ness will be the lower reservoir. The inlet/outlet will have a maximum depth of 15 m, extend approximately 45 m into Loch Ness, and be covered by an inclined screen with 2 mm apertures. During electricity production, the water velocity at the inlet/outlet will be approximately 0.15 ms^{-1}, while during pumping it should be less than 0.15 ms^{-1}. In the inlet/outlet structure, there will also be a mechanism for cleaning the screen, wave walls, a stilling chamber, and the spillway outfall. During the construction of the Red John PSH scheme, a temporary cofferdam will be built to encircle the inlet/outlet at approximately 130 m from the shoreline of Loch Ness.

The Red John PSH scheme will include four waterways to transfer water between the two reservoirs. First, the high-pressure tunnel, with a length of approximately 900 m and an internal diameter of up to 9 m, will transport water between the upper reservoir and the powerhouse. The powerhouse, containing the turbines, will be in the power cavern approximately 200 m below ground. The transformer gallery will also be located in the power cavern. A low-pressure tunnel will transport water from the transformer gallery to the stilling basin in the lower reservoir. It will be approximately 1700 m long and will also have an internal diameter of up to 9 m.

The outflow in Loch Ness during electricity generation will be up to 250 m^3s^{-1}. The inflow during pumping will be up to 170 m^3s^{-1}. This equates to a drop in water level for Loch Ness of 87 mm during pumping and a corresponding, but more rapid, increase during electricity production.

For a more detailed description of the Red John PSH scheme, including the construction of accompanying infrastructure such as access tunnels and roads, please refer to the developer's website (ILI Group 2017).

1.5.3 Loch Kemp PSH scheme

The Loch Kemp PSH scheme has not yet gained planning permission. It is still in the early planning stages, so less information is available about this scheme than the Red John PSH scheme. The Loch Kemp PSH scheme will have a generating capacity of 600 MW. It will use an existing lake, Loch Kemp, as its upper reservoir. Currently, Loch Kemp is a small lake with a maximum depth of 15 m (Murray and Pullar 1908). It contains a population of brown trout and some rainbow trout introduced for fishing (Dell Estate 2023). Loch Kemp will be expanded with four saddle dams between 15 and 30 m high and four minor cutoff dams, raising the loch by 28 m (Ash Design + Assessment 2021).

Additional information about the proposed development is limited. The environmental scoping report indicates that, in addition to the expansion of Loch Kemp to create the upper reservoir, there will be an underground waterway system, including screened intakes, which will transport water from the reservoirs via the powerhouse, a shaft-type powerhouse built on the banks of Loch Ness, an outlet area in the shore of Loch Ness, a jetty and an administrative building, as well as access tunnels and roads (Ash Design + Assessment 2021).

2 Review of the environmental impacts of PSH

There are many ways that PSH can affect local aquatic ecosystems. The exact effects are both site and project specific. It is, therefore, vital to assess the potential impacts of new PSH developments on a case-by-case basis. Nonetheless, we provide an overview of some of the most important physical and biological impacts of PSH on reservoirs reported in the scientific literature.

2.1 Physical impacts of PSH

The most striking visual effect of a PSH scheme is how the water levels of the reservoirs change during pumping and electricity production (Hirsch et al. 2017). Though water levels fluctuate naturally in lakes, abstraction or discharge of water during PSH operation can change the magnitude and rate of water level fluctuations (Zohary and Ostrovsky 2011; Hirsch et al. 2017). In addition to these fluctuations, PSH operation leads to the mixing of water from two separate, and often disparate, reservoirs. Accordingly, the physical environments of the lower and upper reservoirs can be changed by water level fluctuations and the mixing of water from different sources in several ways. Here, we focus on how PSH schemes affect water temperature profiles, flow patterns, erosion rates, turbidity, and nutrient input.

> **Definitions**
>
> **Stratification:** the presence of separate, distinct layers of water in a lake, typically caused by differences in water temperature.
> **Epilimnion:** the upper layer of water in a stratified lake.
> **Hypolimnion:** the lower layer of water in a stratified lake
> **Thermocline:** the boundary between the upper and lower layers of water in a stratified lake.
> **Monomictic:** a stratified lake where the water layers mix once a year.
> **Dimictic:** a stratified lake where the layers mix twice a year.

The water level fluctuations and the mixing of separate bodies of water that result from PSH operation can alter the water temperature profiles of reservoirs, typically causing temperatures to increase, which can be due in part to frictional losses when pumping (Bonalumi et al. 2012). Additionally, these schemes often use deep lakes as reservoirs, which are typically stratified, resulting in the degradation of their natural stratification (Boehrer and Schultze 2008; Bermúdez et al. 2018). Stratification occurs when a warmer, and thus less dense, layer of water ('epilimnion') sits on top of a colder, denser, and deeper layer of water ('hypolimnion'). The transitional depth, where temperatures abruptly change between the epilimnion and hypolimnion, is called the 'thermocline'. During periods of strong stratification, little natural mixing occurs between the epilimnion and hypolimnion (Boehrer and Schultze 2008). However, many lakes only stratify during particular times of the year, and the epilimnion and hypolimnion can mix and merge into a single body during other times. Lakes where mixing occurs twice a year, once in the spring and once in the autumn, are referred to as dimictic lakes, while those where the mixing occurs once per year are referred to as monomictic (Wetzel 2001). Water abstraction or discharge can modify the naturally occurring thermocline in such deep lakes (Weber et al. 2017; Bermúdez et al. 2018; Kobler et al. 2018). In PSH schemes, the extent that the stratification of a reservoir is affected depends on the natural thermal regime of the reservoirs, the depth of the outlet/inlet in each reservoir, and the morphology of the reservoirs (Bonalumi et al. 2012; Bermúdez et al. 2018; Kobler et al. 2018). Whether the inlet/outlet is placed in the epilimnion or hypolimnion will affect how much the reservoir is warmed, and whether the thermocline is affected by abstraction/discharge. When the inlet/outlet for one reservoir is in the epilimnion, but in the hypolimnion for the other reservoir, natural nutrient and dissolved oxygen levels in the reservoirs can be interrupted, as oxygen and nutrient-rich waters from the cold hypolimnion of one reservoir are pumped into the warmer, less nutrient-rich, epilimnion of the other reservoir (Kobler et al. 2018). Furthermore, the degradation of the thermocline is not necessarily equal across the reservoir and can be strongest close to the inlet/outlet (Bermúdez et al. 2018). Reservoirs that naturally have strong stratification are more susceptible to changes in temperature from PSH (Bermúdez et al. 2018). This can be further exacerbated by natural water levels, where reservoirs with shallower depths are more susceptible to temperature changes (Bonalumi et al.

2012; Bermúdez et al. 2018). Under climate change, where ambient temperatures are increasing, alterations to natural temperature profiles and levels of stratification are expected to be affected by PSH more severely (Kobler et al. 2019).

Flow is one of the most important characteristics of aquatic environments. Both the fluctuations of water levels and the abstraction/discharge of water into PSH reservoirs can alter flow patterns (Bermúdez et al. 2017; Müller et al. 2018; Nikolaos et al. 2023). The flow patterns, and corresponding water velocity, depend on whether the PSH is pumping or producing electricity (Bermúdez et al. 2017). The effect of water withdrawal during pumping on flow seems lower than the effect of water discharge during electricity production (Müller et al. 2018), though this may be case-specific. The changes caused to the thermal regime of the reservoirs listed above, as well as changes in flow patterns, can cause changes to ice cover in regions where the lakes freeze in the winter. The onset of ice can be later in the year and may last for shorter durations during the winter (Kobler et al. 2018).

Erosion rates, turbidity, and nutrient input are related impacts of PSH. Fluctuating water levels can lead to higher erosion rates along the reservoirs' shorelines (Hirsch et al. 2017). This can increase the turbidity of the water column and nutrient input if the shoreline substrate contains high levels of organic matter. Furthermore, mixing water between the two reservoirs can alter the turbidity and nutrient content of each reservoir (Hirsch et al. 2017; Kobler et al. 2018). This is particularly the case when one reservoir has naturally higher levels of suspended solids and/or nutrients than the other reservoir, and transfers these during PSH operation (Bonalumi et al. 2011; Bonalumi et al. 2012; Kobler et al. 2018). Higher erosion rates may also cause increased sedimentation rates, which can alter the physical characteristics of the reservoirs' benthos (Hirsch et al. 2017).

2.2 Biological impacts of PSH

Any alterations to the physical environment will influence the biological characteristics of an aquatic ecosystem. The physical changes to reservoirs caused by fluctuating water levels and the mixing of different bodies of water during PSH operation can affect the reservoirs' biota in myriad ways and depend on the magnitude of the physical effects and types of aquatic life present (Hirsch et al. 2017). In general, fluctuating water levels in reservoirs can lead to reductions in biomass and biodiversity over time (Zohary and Ostrovsky 2011; Evtimova and Donohue 2014; Hirsch et al. 2017). Here, we touch on how the physical impacts listed previously can affect habitat availability, primary production, trophic interactions, invasive and non-native species, and migratory aquatic species, which can all lead to biomass or biodiversity reductions over time.

Firstly, water level fluctuations can cause the reduction of reliable habitats within reservoirs. This means that the littoral zone can be reduced relative to the total area and volume of the lake, particularly in steeply sloping lakes where the littoral zone is relatively small. In deep, oligotrophic lakes, the littoral zone is particularly important for the stability of the food web (Hampton et al. 2011). This can lead to reductions in the taxon richness of littoral macrophytes and invertebrates as habitats become limited (Aroviita and Hämäläinen 2008; Hirsch et al. 2017). For example, in Finland, a study of 11 regulated lakes and 12 unregulated lakes revealed that the composition of the littoral macroinvertebrate community varied with the extent that the water levels fluctuated. There, low levels of littoral species richness were associated with higher intensities of water level regulation (Aroviita and Hämäläinen 2008). There has been less research on the impacts of PSH on benthos communities than on littoral communities. Nonetheless, it is possible that sedimentation from erosion, or an increased influx of suspended solids settling on the benthos, can alter the predominant substrate on the bottom of the reservoir, ultimately impacting habitat availability for benthic invertebrates (Hirsch et al. 2017). This will likely depend on the erosion rate and sediment input into the reservoir, as well as the size of the reservoir, but more research is needed. Habitat loss in the littoral and benthic zones can alter the abundance of diverse species, which might, over time, alter the diversity of species in the reservoir (Aroviita and Hämäläinen

2008; Zohary and Ostrovsky 2011). Furthermore, water level fluctuations may pose a threat to fish populations that spawn in tributaries, reducing access to vital spawning habitats.

Next, primary production might also change as the physical characteristics and temperature regimes of the reservoir change. Nutrient input, resulting from erosion or the influx of nutrient-rich water from one reservoir to the other, can cause increases in primary production (Zohary and Ostrovsky 2011; Hirsch et al. 2017). Increased primary production can lead to increased productivity at higher trophic levels, which might increase the biomass of the reservoir. As the reservoir ages, nutrient input might start to decrease, so the increase in primary production may not last (Milbrink et al. 2011). This can ultimately lead to trophic depression and reduced growth rates among species at higher trophic levels, such as fishes (Zohary and Ostrovsky 2011; Milbrink et al. 2011; Hirsch et al. 2017). Conversely, increased turbidity, which may attenuate the depth that light can reach, can adversely affect primary production by limiting photosynthesis. Changes in primary production can propagate upwards through the food web and affect organisms at higher trophic levels. A reduction in lake productivity can cause the biomass of fish species to decline (Hirsch et al. 2017).

Migratory species, such as Atlantic salmon or anadromous brown trout, can traverse lakes and reservoirs on their way to sea. It is well-known that smolts, the migratory juvenile life stage of salmonids, follow the main flow in a river (Coutant and Whitney 2000) and predominantly swim near the surface where the water has a higher velocity (Thorstad et al. 2012). Though their passage through lakes is relatively understudied (Lennox et al. 2021), several studies show smolts struggle to navigate lochs and lakes when there are no directional cues from flow but can regain their sense of direction when the flow begins to increase at the outlet of the lake (Honkanen et al. 2018; Honkanen et al. 2021; Hanssen et al. 2022). Alterations to natural flow patterns during the pumping/discharge regime of PSH schemes can, therefore, become a problem for migratory fishes. It is very possible that fishes such as salmonid smolts may detect the unnatural flow patterns and become attracted to them, thus being 'misguided' away from the outlet of a reservoir they should be aiming for and towards the inlet/outlet of the PSH scheme.

A well-known problem with conventional hydropower schemes that fish face is impingement or entrainment at intakes. Impingement occurs when the flow and resulting velocities into the turbine tunnel is strong enough that the fish get 'stuck' on a rack or screen, while entrainment means the fish gets drawn into the turbine tunnel (Rytwinski et al. 2017; Algera et al. 2020). This appears to be less studied for PSH schemes, but since it is a problem with conventional hydropower schemes it can likely affect fish migrating through PSH reservoirs too. One example where this was studied in a system with a PSH scheme is among juvenile and adult American shad, where juveniles were more likely to be entrained at the PSH facility than adults. The entrainment rate for juveniles was highest during periods of extended pumping, while it tended to be generally much lower for adult fish (Mathur et al. 2018).

Finally, invasive and non-native species found in one reservoir may spread to the other reservoir when the PSH is operating. There have not been many studies that have focused specifically on the spread of invasive/non-native species due to PSH, but the few that do exist suggest that small fish capable of surviving passage via the turbines could be a good candidate for becoming invasive in PSH reservoirs. For example, eastern mosquitofish (*Gambusia holbrooki*), which are considered invasive in many places, have been shown to survive the shear stress and pressure, as well as avoid blade strikes, during a trial where they were subjected to simulated PSH conditions (Doyle et al. 2020). Furthermore, redfin perch (*Perca fluviatilis*), invasive outside of Europe, can survive passage through a simulated PSH scheme, with juvenile life stages fairing particularly well (Doyle et al. 2022). If small invasive fish exhibit the potential to survive passage in PSH schemes, then other aquatic organisms might spread this way too. The spread of invasive species can be mitigated by using screens at the inlets in the reservoirs.

Many of the effects of PSH schemes on abiotic and biotic components of ecosystems are intertwined (**Figure 5**), which can make it challenging to predict how new PSH developments will impact a specific site. Nonetheless, it is clear that PSH schemes can affect every level of the aquatic community, from the phytoplankton at the base of the food web to the piscine predators at the top.

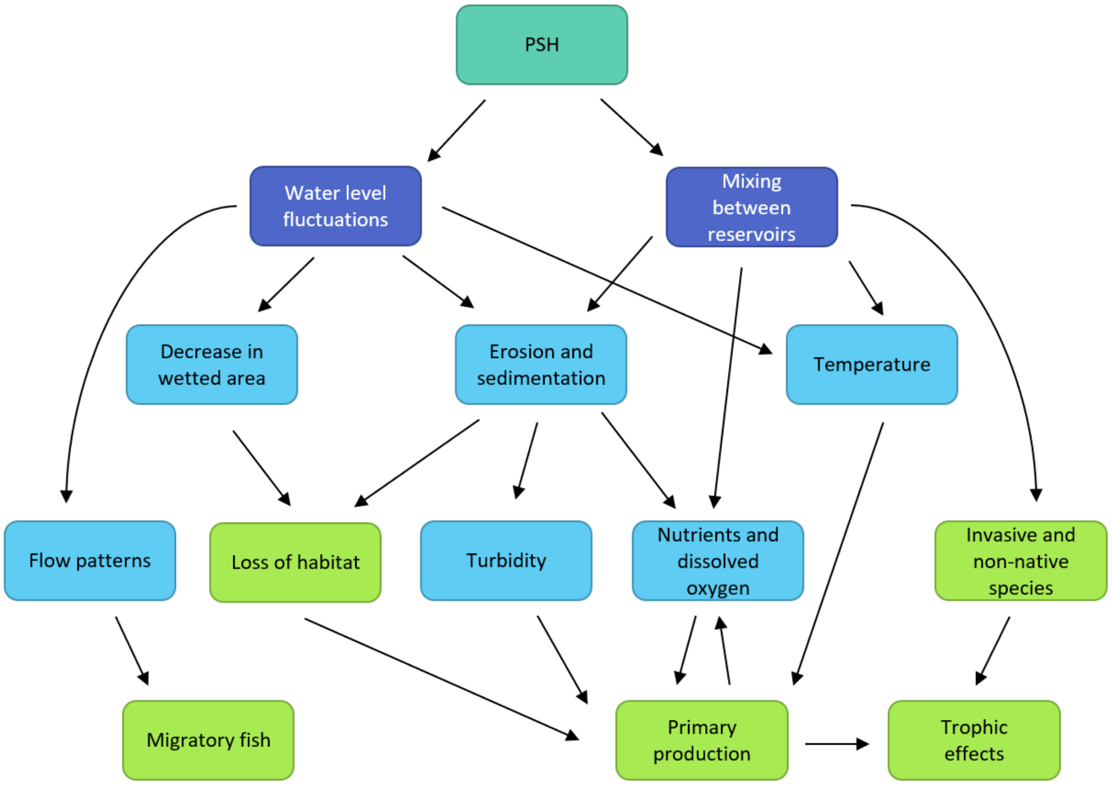

Figure 5. *A flowchart demonstrating the different effects PSH schemes can have on the environment. The two main drivers of the impacts are water level fluctuations and mixing between reservoirs, which are shown in purple. Physical impacts are shown in blue and biological impacts are shown in green.*

3 Potential impacts of PSH in Loch Ness for Atlantic salmon

An environmental impact assessment (EIA) for the Red John PSH scheme was published in November 2018. The EIA assessed the impacts on the development site's geology, terrestrial ecology, aquatic ecology, ornithology, flood risks, the water environment, visual aspects, forestry, archaeology and cultural heritage, socioeconomics and tourism, traffic and transport, and noises and vibrations coming from the site. There has not been an EIA conducted for the Loch Kemp PSH scheme yet. There has, however, been an environmental scoping report, published in December 2021, which includes sections on water management, visual aspects, land use and recreation, terrestrial ecology, ornithology, aquatic ecology, fish, geology, soils, cultural heritage, traffic, noise and vibrations, air quality, forestry, and socioeconomics and tourism.

Here, we describe some of the main findings of these two documents, with a focus on the sections relevant to Atlantic salmon in Loch Ness. We also highlight some potential impacts most relevant to Atlantic salmon that are not covered by these documents.

3.1 Potential impacts identified in the Red John EIA

The Red John PSH EIA chapters most relevant to Atlantic salmon are Volume 2, Chapters 7, 9, and 10. Chapter 7, titled 'Aquatic Ecology', deals most directly with the consequences of the Red John PSH scheme for Atlantic salmon and other aquatic species. Chapters 9 and 10 deal more with the hydrology of the development sites, with Chapter 9 ('Flood Risk and Water Resources') providing information about water levels or flow rates in Loch Ness, River Ness, and the Caledonian Canal, and Chapter 10 ('Water Environment') discussing alterations to the water quality and temperature regime in Loch Ness.

3.1.1 Aquatic ecology

Most information relevant to Atlantic salmon is in Volume 2, Chapter 7 ('Aquatic Ecology') of EIA. Here, we highlight the most relevant points for Atlantic salmon and conclude with a brief synoptic account of some of the impacts listed for other organisms in Loch Ness. For this chapter of the EIA, both desk-based and field studies were undertaken. Most relevant to Atlantic salmon was the fish habitat assessment, which consisted of fifteen site surveys in the area most likely to be impacted by the development, intending to assess spawning habitat potential. These surveys were conducted from 19 to 21 June, meaning there were no observations of potential seasonal variations in these sites. It should also be noted that although the intention was to assess spawning habitat availability, the EIA does not state which fish species it regards as likely to be spawning during the study dates. From the site surveys, it was observed that Atlantic salmon and sea trout are unlikely to use Loch Ness for spawning, but that these species do transit the loch during their migrations. The EIA also notes that 'significant numbers of smolts may be present close to the tailpond [meaning Loch Ness] inlet/outlet both during construction and operation'. Yet, the EIA further states that more detailed studies of smolt and adult Atlantic salmon migratory routes in Loch Ness should not be required. To date, there have not been any detailed studies of Atlantic salmon movement within Loch Ness in peer-reviewed scientific publications, so it appears that such studies are, in fact, needed to better inform the developers of the potential risks to the 'significant' numbers of smolts that may be near the PSH's Loch Ness inlet/outlet. The possible impacts of the Red John PSH documented in the desk study and site surveys include effects during construction, operation, and decommissioning.

3.1.1.1 Construction

During construction, it is noted that building the Cofferdam and temporary jetty may cause the following impacts on Atlantic salmon as they migrate through Loch Ness:

- Injury or mortality from construction, piling, and de-watering

- Injury from piling noise
- Avoidance reactions from Atlantic salmon

These are predicted to culminate in major temporary adverse effects for the migrants. Given this, it is particularly important to better understand the migratory routes of these fish, requiring detailed scientific studies of salmon movement within Loch Ness.

Another effect that might affect migrating salmonids during construction is the lighting on the site for excavating the tunnel, access to the lower and upper reservoirs, and boat navigation at the jetty. The EIA states that directional cowling and a restricted schedule for using lights will mean that they will have a negligible impact. This is important, as lighting is known to affect the migratory timing of smolts elsewhere in the UK (Riley et al. 2012).

There is some information about other effects from construction related to Atlantic salmon in the loch, including decreases in water quality due to the transport of excavated sediments and the potential spread of invasive or non-native species. These are considered by the EIA to have low impacts on the Atlantic salmon.

3.1.1.2 Operation

There are several ways that the operation of the Red John PSH scheme might affect Atlantic salmon. The most obvious way is the effect of the inlet/outlet structure on migrating smolts and adults. The EIA notes that the 2 mm apertured screen will prevent fish from entering the PSH and that the 0.15 ms^{-1} water velocity at the inlet/outlet is below the sustained and burst swimming speeds of these fish. It also states that the PSH scheme will likely operate no more than once per day. Thus, the EIA concludes that the risk of impingement at the screens during migration is negligible due to the low water velocities and infrequent operation of the PSH. From this, it concludes that there will be no adverse effects on the freshwater pearl mussel populations of the River Moriston SAC, as there will be no adverse effects on their salmonid hosts. Nonetheless, the potential for the inlet/outlet to 'distract' migrating fish away from the most efficient migration routes, by providing a flow stimulus otherwise lacking in the loch, is barely touched upon. There is a brief discussion that the discharging water entering the loch during energy production might distract adult salmon, but then the screen at the outlet is considered sufficient to prevent serious effects on these fish (i.e., impingement/entrainment). This is true in the sense that any adult salmon attracted to the outlet will not be entrained, still, there is no consideration of the impacts such a distraction might have on slowing down their migration to the rivers they use for spawning. It is likely that adult salmon will be attracted to, and therefore distracted by, such a flow stimulus. Furthermore, smolts are also known to follow the flow (Thorstad et al. 2012), but the impact of pumping, causing a flow stimulus out of the loch towards the upper reservoir, is not considered. Migration timing is important for smolts, and distractions may cause migration delays, meaning they arrive at sea later than they otherwise would. This could have negative fitness and survival consequences (Rikardsen and Dempson 2011). Additionally, spending longer than necessary in Loch Ness can expose smolts to predators, such as the loch's ferox trout or pike (Maitland, Smith, and Adair 1981; Grey et al. 2002). Further consideration of migration delays caused by distractions at the inlet/outlet are therefore critical. It also seems premature to assume there will be no adverse effects on the River Moriston SAC when the implications of alterations to the flow navigation cues in Loch Ness for salmon migration are not fully considered and investigated.

According to the EIA, during operation the water level in Loch Ness will vary by 87 mm. Effects of fluctuations in the water level during smolt and adult Atlantic salmon migration are not considered in the EIA. Though the direct effects of pumping/producing might be localised to the area nearest the inlet/outlet, as suggested by the EIA, the effects of water level fluctuations will likely be felt throughout the loch. How this might alter natural flow patterns in the loch, important for fish migration, is another topic that the EIA would benefit from considering. Furthermore, for smolts to enter River Ness on their seaward migrations, they must pass the Ness Weir. Though salmon are known to pass the Ness Weir, it is likely much more challenging for salmon, particularly smolts, to pass the weir when water levels are low. The EIA does not consider how fluctuating water levels might affect fish passage at this weir. Nor does the EIA consider how the simultaneous operation of the Red John PSH scheme and the current Foyers scheme will drop the water level in the loch, and how this will cumulatively affect fish passage at the weir.

Notably, the EIA states that the Controlled Activities Regulation license, provided by SEPA and required for construction, might impose limitations on the timing of construction activities to minimise the disruption caused to migrating salmonids. Though operation will undoubtedly also have impacts on these fish, there is no indication from the EIA that operation schedules will similarly be adjusted to account for the salmonid migration periods.

Again, there is some other information relevant to Atlantic salmon in the 'operation' section of the EIA. The main effect is considered to be the spread of invasive and non-native species during the operation of the Red John PSH. The EIA concludes this is likely to have a minor impact on the migrating salmonids, as it notes that salmon already coexist with invasive species, such as the crustacean *Crangonyx pseudogracilis*, in Loch Ness.

3.1.1.3 Decommissioning

It is not anticipated that the PSH will need to be decommissioned, but the EIA does detail some possible effects should decommissioning occur. In Loch Ness, possible effects might include the disturbance of the loch's substrate, the movement of sediment, and injury or mortality to fish present when the work is ongoing. However, because the work associated with decommissioning is thought to be quite localised within the loch, these impacts are expected to be negligible.

3.1.1.4 Other considerations for aquatic ecology

The aquatic ecology chapter of the EIA makes four recommendations for further surveys before the start of construction, including electric fishing surveys in the small tributaries located within the development site, mainly targeted at resident brown trout, a repeated macroinvertebrate study during the autumn (the first study was conducted during the summer), a survey on how the cofferdam and jetty will affect the presence of invasive species in Loch Ness, and finally a walkover survey of watercourse crossing for invasive species. Studies related to salmonid migratory routes in the loch, alterations to flow patterns during operation near the inlet/outlet, and alterations to flow patterns across the loch due to water level fluctuations are notably missing. The EIA also suggests that the inlet/outlet be monitored regularly during operation for issues with the inlet/outlet screen and that distractions caused to migrating fish also be monitored. Though the EIA suggests tracking studies of Atlantic salmon in Loch Ness are unnecessary, it will be challenging to determine whether these fish are being distracted by the PSH operation without baseline data on their migration routes before PSH construction.

While we have focused on impacts on Atlantic salmon as they migrate through Loch Ness, there is potential for the construction and operation of the Red John PSH scheme to also impacts other aspects of the Loch's ecology. Though these are not extensively reviewed here, the other main topics in this chapter of the EIA were related to macrophytes, macroinvertebrates, and invasive and non-native species. During construction, operation, and decommissioning, the EIA suggests there will be negligible impacts on these other organisms. However, like the Atlantic salmon and other fish species, these findings are based on brief site surveys, which ultimately provide a 'snapshot' of the ecological characteristics of Loch Ness, and some desk-based studies. Thus, additional studies over a longer term are definitely required to make a better account of seasonal variations in the loch's ecology.

3.1.2 Water environment

Volume 2, Chapter 10, of the EIA deals with the 'water environment', including impacts on surface water quality, groundwater quality, and hydromorphology. Though this chapter described the possible impacts of the PSH scheme on various water bodies in the development area, the main points that pertain directly to Loch Ness are outlined here. Firstly, there is a section on the increased loading of suspended sediments in Loch Ness. This could result from the construction of the PSH as trees and shrubs are cleared from the development site, leading to soil erosion. Furthermore, fine sediment might come from run-off from earth stockpiles, the dewatering of excavations, mud deposits, and other sources related to construction works. The EIA also mentions the potential build-up of sediments or other organic matter in the upper reservoir if the PSH is not operated regularly. This could be another source of suspended matter in Loch Ness. However, the EIA considers the risks of fine sediment input into Loch Ness to be low, due to the very large size of the loch. Such sediments are expected to diffuse and not have an impact. One overlooked aspect is the potential for littoral erosion rates to increase with the water level fluctuations experienced in the loch during pumping/ electricity production. This could potentially also contribute to suspended solids in the area. It also does not consider how such matter might settle on the benthos of the loch, and whether this might affect the physical characteristics of the loch bed.

Furthermore, this chapter considers possible changes to the thermal profile of Loch Ness and its stratification regime. This chapter of the EIA states that Loch Ness is a dimictic lake, but other sources suggest that Loch Ness is a monomictic lake that becomes weakly stratified in June (Smith et al. 1981; George and Winfield 2000; Cooper et al. 2000). Whether Loch Ness is monomictic or dimictic needs to be clarified to better understand how the PSH may affect its stratification. The EIA also states that the outlet in Loch Ness will be above the thermocline without providing evidence of the depth of the thermocline. It also suggests that the water from the upper reservoir is unlikely to cause warming in the epilimnion of Loch Ness without stating the anticipated temperatures in the upper reservoir. It suggests that during a long period of the PSH not being used, where the water sits in the upper reservoir, the upper reservoir might heat up to 5.5 ºC before being discharged into Loch Ness. Though this might be within the range of normal temperatures found in the surface waters of the loch, seasonal variation in the temperature regime should be taken into account. Generally, there is little supporting evidence presented to underly the assessed impacts of the PSH on the thermal profile of Loch Ness. Quantitative modelling of the temperature regime in the loch throughout the year, along with how the temperature regime will change depending on operation schedules and depth of the inlet/outlet is crucial to clarify the effect of the proposed PSH scheme on Loch Ness.

3.1.3 Flood risk and water resources

The last chapter of the EIA pertinent to the impacts the Red John PSH scheme might have on Loch Ness and its ecology is Volume 2, Chapter 9 (‘Flood Risk and Water Resources’). It details an assessment of the possibility of flooding and some risks to water resources throughout the area. It describes how Scottish and Southern Energy must release water from elsewhere in the catchment as compensation flows for the River Ness when Loch Ness is low. Operational effects of the Red John PSH scheme include a reduction in water levels in Loch Ness, which in turn can impact the water level of the Caledonian Canal and the flows in the River Ness. During pumping, a maximum of 4.9 x 10 m^3 of water can be abstracted from Loch Ness. This would occur in under eight hours. The authors of the EIA conducted a simple analysis under two scenarios (one with normal and one with low water levels in Loch Ness) to demonstrate that water levels could take 12 days to naturally recharge after pumping (assuming the upper reservoir does not discharge in the meantime). They suggest that this could lead to water levels in Loch Ness falling below those required to operate the Caledonian Canal, meaning Scottish and Southern Energy would need to release water from elsewhere in the catchment. However, the EIA then states that the impact of these changes to the water level in Loch Ness will only be short-term. This information about the fluctuations in water levels in the loch, and knock-on effects for the flows in the Caledonian Canal and River Ness, is written in isolation of the ecology of the loch. A better synthesis of how this information might play into the ecological impacts is required.

3.2 Potential impacts identified in the Loch Kemp environmental scoping report

The chapters of the Environmental Scoping Report for the Loch Kemp PSH scheme that are most relevant to Atlantic salmon in Loch Ness are Chapters 6, and 12 (titled ‘Water Management’, and ‘Fish’, respectively). Additionally, Chapter 11 (‘Aquatic Ecology’) deals with the non-fish aspects of ecology, which may not be directly relevant to Atlantic salmon but are relevant to the wider aquatic ecology of Loch Ness. The scoping report lays out what information ought to be included in an EIA. Here, we outline the main points from these chapters focused mainly on points relevant for Atlantic salmon. We will discuss these chapters in the order in which they are most relevant to Atlantic salmon in Loch Ness. Generally, there is little information given in this scoping report. Because of that, we provide a quick summary and consider the knowledge gaps in the impacts listed in the scoping report together with knowledge gaps for the Red John PSH scheme in Section 4.

3.2.1 Fish

The proposed scope of the EIA for the Loch Kemp PSH scheme concerning the fish in Loch Ness includes:

- Effects during construction:
  - Habitat loss/habitat fragmentation
  - Underwater noise altering natural fish behaviour
  - Mortality from decreased water quality due to runoff/sedimentation and pollution
- Effects during operation:
  - Habitat loss due to increased rate of water fluctuations in Loch Ness
  - Changes to fish migratory behaviour in Loch Ness
  - Changes to habitats due to changes in sediment transport
  - Injury or mortality to fish caused by impingement or entrainment
  - Spread of invasive or non-native species
  - Changes in fish behaviour due to noise from pumping

3.2.2 Water Management

The proposed scope of the EIA about water management, that is relevant to Atlantic salmon in Loch Ness, includes:

- The proposed operation schedule of the PSH
- Proposed abstraction and discharge rates

3.2.3 Aquatic ecology

The proposed scope for the EIA with regard to the aquatic ecology of Loch Ness focuses on macroinvertebrates and bryophytes. It includes:

- Effects during construction:
  - Habitat fragmentation and pollution effects for macroinvertebrates
  - Effects of pollution, sediment transportation, and alteration of morphological conditions on bryophytes
- Effects during operation:
  - Effects of water fluctuations on macroinvertebrates
  - Spread of invasive or non-native species during pumping

4 Knowledge gaps

There are some considerable knowledge gaps about how the proposed PSH schemes will affect Loch Ness. It is striking that the Foyers PSH scheme has been in operation since 1974, but few studies have investigated potential impacts of the scheme on the ecology of Loch Ness. There is currently not enough concrete evidence to determine the extent to which the proposed PSH schemes will affect Atlantic salmon as they migrate through Loch Ness. The focus on fish habitat in Loch Ness in the Red John PSH EIA is a missed opportunity, when Loch Ness is so important for migrating fish that are not resident and using it as a habitat, but rather as part of their route to the sea. Concerningly, there is also a lack of knowledge on the cumulative impacts of the three PSH schemes, Foyers, Red John, and Loch Kemp, on the ecology and Atlantic salmon of Loch Ness. Thus, some significant knowledge gaps, with an emphasis on the cumulative effects of the three projects, are identified below.

4.1 What changes will the proposed projects cause to the natural flow patterns in Loch Ness?

There is not enough information about the ways the Red John PSH scheme and the Loch Kemp PSH scheme will affect the natural flow patterns in Loch Ness during pumping and electricity production. If these two PSH schemes are operating simultaneously with the current Foyers PSH scheme, these three projects will likely alter the natural flow patterns in Loch Ness in a way that will have knock-on effects on the natural processes (e.g., erosion rates, turbidity, nutrient inputs) and the aquatic organisms in the loch. It is already known that migratory aquatic organisms, such as Atlantic salmon smolts, find large lakes challenging to navigate (Honkanen et al. 2018; Honkanen et al. 2021; Hanssen et al. 2022). Instead of discussing how alterations in flow patterns will affect migrating salmonids, potentially causing delays that could expose them to predation pressures or cause energy depletion, the Red John EIA focuses on how the 2 mm aperture screen will prevent entrainment, and how the water velocity though the screen will be low enough to avoid impingement. This is not adequate for examining how changes in flow patterns are going to affect migrating smolts and adult Atlantic salmon. A better understanding of the PSH schemes' effect on flow patterns is critical to predict whether alterations in the natural flow patterns will be 'distracting' for migrating salmonids.

4.2 What is the spatial distribution of smolts migrating through Loch Ness?

It is not yet known how smolts migrate through Loch Ness. Studies of smolts in other Scottish lochs suggest they take indirect, or even random, migration routes across these big lakes (Honkanen et al. 2018; Honkanen et al. 2021). Once the new flow patterns caused by the PSH are known, this information needs to be coupled with information about the smolt migration routes through Loch Ness to predict whether the smolts are likely to pass close to the PSH schemes. This then needs to be used to determine the extent to which smolts may be led astray by the three PSH schemes. It is perplexing that the Red John PSH scheme EIA claims tracking studies are not needed as such studies should be a matter of priority.

4.3 How does the current Foyers PSH scheme impact Atlantic salmon migrating through Loch Ness?

The Foyers PSH scheme has been in operation since 1974, yet, to our knowledge, how this scheme affects salmon migrating through Loch Ness has not been thoroughly studied. This is a missed opportunity to learn how the flow patterns caused by pumping and electricity production at Foyers affect salmonids in the area. Such data should be gathered to provide important background information for assessing the possible impacts of the proposed new PSH schemes on migrating Atlantic salmon.

4.4 How will so many PSH schemes affect the temperature profile of Loch Ness?

It is well known that PSH schemes can alter the temperature profiles of their reservoirs, even causing changes to the depth and stability of the reservoirs' thermoclines (Bonalumi et al. 2012; Kobler et al. 2018). The EIA for the Red John PSH scheme claims that operations of this scheme will not impact the thermocline but provides no concrete evidence to back this assertion. More rigorous research is required to examine how each proposed PSH will affect the thermal profile of Loch Ness and how the simultaneous operation of three PSH schemes in Loch Ness will affect the stability of the thermocline.

4.5 How will climate change interact with the changes to the flow patterns and temperature profile of Loch Ness?

Climate change is likely to trigger changes to rainfall and weather patterns in the UK, which will alter flow regimes in aquatic ecosystems (Watts et al. 2015). Rising temperatures will also affect the temperature regimes of lakes, altering the phenology of stratification in large deep bodies of water (Woolway et al. 2021). Yet, how the looming effects of climate change and the potential impacts of the PSH schemes will affect Loch Ness are unknown and need to be considered.

4.6 Will the operation of the proposed PSH schemes lead to gas supersaturation in Loch Ness?

It is increasingly recognised that gas supersaturation, a possible side effect of hydroelectricity production, has serious lethal and sublethal effects on fish (Stenberg et al. 2022; Li et al. 2022). Gas supersaturation occurs when air mixes with water as it passes through spillways or through tunnels and turbines. Fish exposed to supersaturated water can develop gas bubble disease (Weitkamp and Katz 1980). Neither the EIA for the Red John PSH scheme, nor the environmental scoping report for the Loch Kemp PSH scheme, discussed whether gas supersaturation may be a problem during electricity production. The potential for gas supersaturation and possible risks to migrating and resident fish is something that requires evaluation.

4.7 Recommendations for future studies

With these gaps in mind, further studies are recommended to better understand how the proposed projects might affect the Atlantic salmon transiting Loch Ness, as well as the loch's wider ecology. We recommend:

1. **hydraulic modelling of the loch** under different scenarios to understand how flow patterns will be altered. Such scenarios should include pumping and producing phases, different initial water levels in Loch Ness, and all three PSH schemes operating at the same time
2. **tracking studies of smolts and adult Atlantic salmon** migrating through Loch Ness to understand the routes they take across the loch and the extent to which they will encounter the PSH schemes
3. **modelling the effect of operating one, two, or three of the PSH schemes on the temperature regime and thermocline** across the seasons, and under different climate change scenarios
4. studying whether **gas supersaturation** in Loch Ness will result from operating the proposed PSH schemes, which is currently overlooked in the EIA and environmental scoping reports
5. **long-term monitoring** of the site, and chronicling changes to the physical characteristics of the loch, because there is a lack of long-term studies on PSH reservoirs currently in the literature. Long-term monitoring will also aid in understanding how climate change is

interacting with the PSH schemes to cause alterations to the physical environment and ecology of Loch Ness.

Finally, the effects of the PSH schemes must not be studied in isolation, but rather the cumulative impacts of the Foyers, Red John, and Loch Kemp PSH schemes operating concurrently must be considered together.

5 Mitigative and offsetting measures

There are several measures that the PSH companies can undertake to help mitigate or offset adverse effects these developments may have on Atlantic salmon in Loch Ness.

5.1 Adjust operation schedule to account for important migratory periods

Smolts and adult spawners must migrate via Loch Ness. With the likelihood that the PSH schemes will cause directional confusion for these fish, potentially delaying their journey and exposing them to predation, PSH operators should be aware of the Atlantic salmon migration periods and adjust their schedules accordingly (Fjeldstad et al. 2021). For example, limiting or ceasing operations during smolt migrations would be mitigative. Alternatively, it is well-known that most smolts, particularly early in the smolt run, migrate at night (Thorstad et al. 2012). Eliminating nighttime operations during this period could be a beneficial mitigation measure.

5.2 Aid in successful navigation of smolts throughout the catchment

As noted in Chapter 1, a considerable number of smolts that leave River Garry never reach the sea. The early results from the Moray Firth Tracking Project indicate that smolts that exit Loch Oich via River Oich, instead of via the Caledonian Canal, have higher chances of reaching Loch Ness. Therefore, blocking smolt passage in either direction by the Caledonian Canal could be a beneficial offsetting measure. There are several methods that could accomplish this, including physical barriers or behavioural guidance systems.

5.3 Improvements to existing fish passage infrastructure

The Ness Weir currently separates Loch Ness from the River Ness. Atlantic salmon adults and smolts are likely to have trouble passing the weir if the water level in the Loch is low. Ensuring adequate flows over the weir is one way to make it more easily passable to migrating fish. The other way would be to update the current fish passage structure in the weir to be more efficient even at low water levels in the loch.

Additionally, the Moray Firth Tracking Project revealed that downstream migrating smolts have lower success rates when migrating down the Caledonian Canal than using the natural rivers to exit lochs. There is currently a smolt bywash in the Caledonian Canal downstream of Loch Ness. During a field visit in June 2023, it appeared very little flow entered the bywash. Since salmon use flow as a navigational cue, it is likely that this bywash is unattractive to stray salmon. Improvements to this infrastructure, including ensuring adequate flow to attract the fish, could help smolts that enter the canal return to River Ness, where their chances of making it to the Moray Firth appear higher.

Finally, infrastructure could be improved at existing hydropower facilities to increase salmon survival as another offsetting measure. For example, it is believed that smolts passing the Invergarry Power Station get delayed and suffer mortality when trying to locate the fish pass, so it has been proposed that the smolt screens should be removed and the smolts allowed to pass via the turbines. There is some evidence that smolts that pass through the Invergarry Power Station can survive such a passage, but others succumb to mortality from turbine strikes or attain sublethal injuries such as scale loss. Turbine passage is generally known to cause injury or mortality to migrating salmonids (Mueller et al. 2017, Cox et al. 2023). Improvements to safe passages would be preferrable to forcing smolts to migrate via turbines.

5.4 Removal of unnecessary barriers

Barriers in rivers, such as dams and weirs, hinder migration for Atlantic salmon smolts and adults. Removing barriers can improve migration time and survival (Birnie-Gauvin et al. 2019). Thus, an offsetting measure that would help Atlantic salmon populations in the rivers of the Ness Catchment is removing redundant barriers to improve river connectivity for migrating salmonids. For example, though the weir at Ceannacroc Heck has a fish ladder, the weir itself appears to be redundant. It is a good example of a barrier to salmon migration that should be removed to aid in successful migration and would be a valuable offsetting measure for the impacts of the proposed PSH schemes.

6 Conclusions

To conclude, the effects of PSH schemes on aquatic environments can be complex. Such effects might be challenging to generalise, but undertaking case studies to predict how the PSH scheme might affect specific sites is certainly possible. In the case of Loch Ness, there are many unknowns regarding how the proposed Red John and Loch Kemp PSH schemes will affect the broader Loch Ness ecosystem, specifically the migrating Atlantic salmon smolts and adults passing through. Nonetheless, it should be possible to better ascertain some of these effects through a more rigorous assessment, including tracking migrating salmonids in the loch and modelling expected changes to the flow patterns and temperature regimes. Unfortunately, the current EIA and environmental scoping reports for the proposed PSH projects lack concrete evidence to back up claims that salmon will not be significantly impacted. Using the current PSH in Loch Ness as a model to understand how these fish are being affected now could be a good starting point. Investing in mitigative measures, like adjustments to operational schedules during migration, and offsetting measures, such as improving fish passes in the system or removing unnecessary barriers, would help to enhance this important population of Atlantic salmon.

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