March 2025

Glen Earrach Pumped Storage Hydro

Environmental Impact Assessment Report

Volume 5: Appendices
Appendix 10.6: Thermal Stratification Literature Review

Glen Earrach Energy Ltd

Quality information

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Issue History

Issue	Issue date	Details	Authorized	Name	Position
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Glossary

Term	Definition
Monomictic	Lakes that exhibit one circulation period (usually in the spring/early summer) in addition to the period of stratification and are common in temperate latitudes when there is no ice cover during the winter.
Epilimnion	A well-mixed, warmer, and thus less dense, layer of water that sits on top of the mesolimnion and hypolimnion during the stratification, between which there is little mixing.
Mesolimnion	The transitional depth, where temperatures abruptly change between the epilimnion and hypolimnion.
Hypolimnion	Typically, a colder, denser body of water at depth and beneath the mesolimnion and epilimnion during a period of stratification, with little mixing with above layers.
Thermocline	The steep temperature gradient through the metalimnion during stratification.
Mixolimnion	The water column state when it is isothermal (i.e. fully mixed)
Internal seiche	Wind induced, full water body internal rocking motion that can lead to mixing at the margins of the lake in a process known as entrainment.
Euphotic zone	The euphotic zone (or photic zones) is the layer of a lake where enough light penetrates to allow net primary production, meaning the rate of photosynthesis exceeds the rate of respiration.
Plankton	Plankton are free-floating small or microscopic organisms, which can be further divided into phytoplankton and zooplankton.
Phytoplankton	Phytoplankton are autotrophic organisms (i.e. self-feeding) that are otherwise known as ‘primary producers’ and include photosynthesising bacteria (i.e. cyanobacteria) and single celled organisms such as diatoms.
Zooplankton	Zooplankton are heterotrophic organisms and may prey on phytoplankton and thus can play an important role in preventing harmful algal blooms from occurring.

1 Introduction and Approach

1.1 Introduction

1.1.1 Glen Earrach Energy Ltd (GEE) proposes to construct a pumped-storage hydropower (PSH) scheme (henceforth the ‘Proposed Development’) located on the northwest side of Loch Ness, approximately 9.5 km to the south of Drumnadrochit, and 6.5 km north of Invermoriston. The Proposed Development will have a storage capacity of approximately 34,000 megawatt hours (MWh) subject to final configuration of the Headpond, with approximately 2,000 megawatts (MW) of installed electrical pumping capacity and 1,800 MW of installed electrical generating capacity (both subject to final pump-turbine selection), with an average gross head (vertical distance between Headpond and Tailpond) of approximately 480m.

1.2 Purpose of This Report

1.2.1 The Ness District Salmon Fishery Board (NDSFB) commissioned a report in 2023 by the Norwegian Institute for Nature Research (NINA) entitled ‘*A review of the environmental impacts of proposed pumped storage hydropower projects in Loch Ness: implications for migrating Atlantic salmon*’. This concluded that there are several knowledge gaps in understanding the potential impacts of PSH projects in isolation and cumulatively on Loch Ness, and in the context of future predicted climate change. One area of consideration was how these PSH schemes would influence seasonal stratification. This knowledge gap means that there is potential uncertainty in the impact assessment of PSH schemes on Loch Ness. The NDSFB have referred to these issues in consultation on the Proposed Development.

1.2.2 In response to the NDSFB consultation, this literature review provides a synopsis of relevant published information on the potential effects of the operation of a PSH scheme(s) on seasonal lake stratification. It reviews the potential vertical and temporal changes in water column structure and deep-water mixing and then considers what the implications might be for water quality, biological processes and aquatic organisms. Baseline information on the physical character of Loch Ness is also presented as this is relevant to the interpretation of proxy studies. The implications of future climate change are also discussed.

1.2.3 In addition, this appendix includes information on other PSH projects in Scotland and elsewhere in the world as this also provides insights into how lake stratification may be impacted and how these issues have been investigated.

1.2.4 Overall, this literature review has been prepared to support the impact assessment presented in the Environmental Impact Assessment Report (EIAR) **Chapter 10 Water Environment (Volume 2: Main Report)**. Potential impacts on habitats and fish (e.g. such as the loss of shoreline habitats due to the construction of new structures or increased fluctuation in water levels) are not considered by this review. Please refer to **Chapter 9 Aquatic and Marine Ecology (Volume 2: Main Report)** and associated appendices for information on these possible effects. In addition, hydrology and water resource issues are considered in **Chapter 11: Flood Risk and Water Resources.**

1.3 Approach

1.3.1 The online literature review has sought to identify and review relevant information from a range of sources using a selection of key words as set out in **Table 1 Literature search key words**. The references included within each relevant source were also reviewed for additional relevant papers.

Table 1 Literature search key words

Type of source	Key words searched
Published academic papers/journals	• Loch Ness **and** 'water quality', 'temperature', 'thermal / stratification', 'thermocline', 'internal seiche', 'hydrodynamics', 'modelling', 'aquatic ecology', 'plankton', 'fish', and 'algal blooms / cyanobacteria'. • Pumped storage hydro / hydropower **and** 'water quality', 'temperature', 'thermal / stratification', 'thermocline', 'internal seiche', 'hydrodynamics', 'modelling', 'aquatic ecology', 'plankton', 'fish' and 'algal blooms / cyanobacteria'. • Temperate lakes **and** 'water quality', 'temperature', 'thermal / stratification', 'thermocline', 'internal seiche' • Climate change **and** 'thermal / stratification', 'thermocline', 'internal seiche'
Online data resources or academic lake modelling forums/case studies	• General search. • Pumped storage hydro **and** 'data', 'impacts'
Published information on other existing or proposed pumped storage hydro schemes	• Known existing/proposed developments (i.e. Loch na Cathrach (formerly Red John), Balliemeanoch, Cruachan 2, Loch Kemp, Coire Glass, Corrievarkie, Foyers, Glenmuckloch, Sloy, Dinorwig, Ffestiniog, Earba, and Fearna). • General search using 'Pumped Storage Hydro' and 'Hydro Power Plant'.

1.4 Structure of This Report

1.4.1 The results of the literature review and the remainder of this report are set out as follows:

- **Section 2 Loch Ness** – provides a summary of the physical characteristics and baseline water quality and aquatic ecology of Loch Ness where it is relevant to the potential assessment of adverse impacts of PSH schemes on stratification.
- **Section 3 Potential Impacts** – presents a review of published studies considering the impact of PSH schemes on stratification, and at a high-level, what the implications for water quality, biological processes and aquatic ecology could be if stratification changes occurred.
- **Section 4: Influence of Climate Change** – this section considers how climate change may affect water bodies that stratify and how the operation of PSH schemes may affect this.
- **Section 5 Review of Other Pumped Storage Hydropower Schemes** – provides a summary of other existing and proposed PSH schemes in Scotland and further afield highlighted whether there was any assessment of potential impacts on stratification, and if so, how the impacts were assessed.
- **Section 6 Summary and Conclusions**.

2 Loch Ness

2.1 Overview

2.1.1 Loch Ness lies within the Great Glen fault line that cuts across northern Scotland from the Moray Firth in the north to the Firth of Lorne in the south (see **Plate 1 Loch Ness viewed from Dores looking southwest (July 2024)**. It is the largest water body in Great Britain by volume containing c. 7,452 Mm^3 with a mean residence time of c. 2.8 years (Maitland, 1981[1]). It is approximately 39 km long, with a relatively narrow mean width of c.1.45 km, and maximum width of c. 2.7 km. It is steep sided on both shores and very deep, reaching a maximum depth of c. 227 m (Young and Shine, 1993 cited in Jones et al.,1997[2]) with a mean depth of c. 132 m. The loch is divided into two main basins each reaching similar maximum depths either side of a low sill at Foyers formed by siltation from the River Foyers, but where depths are still around 150 m (Thorpe, 1977[3]). It is also aligned on a northeast-southwest axis meaning that it is exposed to prevailing southwesterly winds. There are a number of watercourses that flow into the loch, with the largest being the rivers Oich, Enrick, Moriston, Tarff and Foyers. Water levels are also influenced by several man-made structures including the Ness Weir (otherwise known as Dochfour Weir) and developments such as the existing Foyers Power Station that has been in operation since 1974 and the SSE Great Glen Hydro Scheme (see **Chapter 11: Flood Risk and Water Resources** for further details). Finally, Loch Ness is also nationally important for tourism.

Plate 1 Loch Ness viewed from Dores looking southwest (July 2024)

2.2 Water Column Structure

2.2.1 This literature review is concerned with monomictic stratification in temperate lakes only, as that is the pattern exhibited by Loch Ness. Stratification occurs predominantly when a warmer, and thus less dense, layer of water (the ‘epilimnion’) sits on top of a colder, denser, and deeper layer of water (the ‘hypolimnion’) during the warmer months of the year typically between late spring/early summer and early/mid-autumn. The transitional depth, where temperatures abruptly change between the epilimnion and hypolimnion, is called the metalimnion. The steep temperature gradient through the metalimnion is referred to as the ‘thermocline’ (Dodds, W.K., 2002[4]). Monomictic lakes exhibit one circulation period in addition to the period of stratification and are common in temperate latitudes when there is no ice cover during the winter. Outside of the stratification period the water column may be described as ‘fully mixed’ and ‘isothermal’ (also known as the mixolimnion), although that is a relative generalisation.

[1] Maitland, P.S. ed., 2012. The ecology of Scotland’s largest lochs: Lomond, Awe, Ness, Morar and Shiel (Vol. 44). Springer Science & Business Media.

[2] Jones, R.I., Laybourn-Parry, J., Walton, M.C. and Young, J.M., 1997. The forms and distribution of carbon in a deep, oligotrophic lake (Loch Ness, Scotland). Internationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen, 26(2), pp.330-334.

[3] Thorpe, S.A., 1977. Turbulence and mixing in a Scottish loch. Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences, 286(1334), pp.125-181.

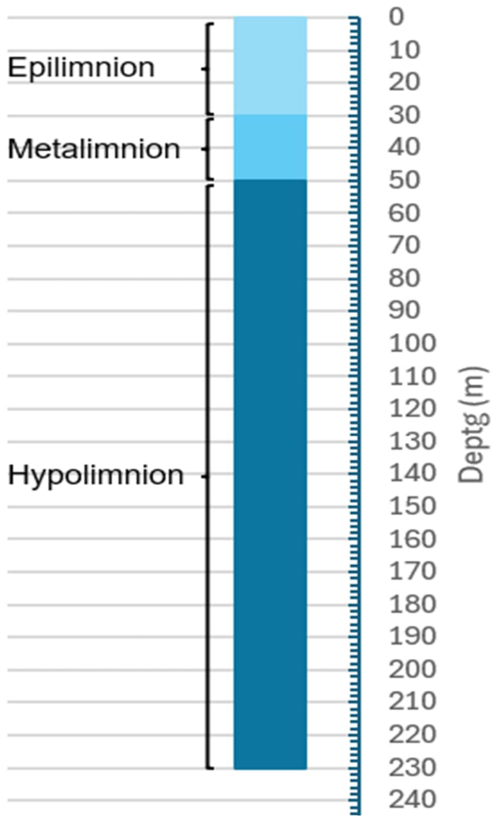
[4] Dodds, W.K., 2002. *Freshwater ecology: concepts and environmental applications*. Elsevier.

2.2.2 The depth of the mixed layer, or epilimnion, depends on the balance between stratifying and mixing forces. Deepening is driven by wind mixing and convective cooling, and shallowing driven by warming from solar radiation especially when there are extended periods of light winds (Wüest and Lorke, 2003[5]). These factors interact and the system is dynamic and will vary over the summer but also between years and in response to longer term changes in climate. During periods of strong stratification, little natural mixing occurs between the epilimnion and hypolimnion (Boehrer and Schultze 2008[6]). Seasonal stratification is therefore a fundamental concept that underpins limnological processes in deep freshwater lakes, with implications for water quality, biological processes and aquatic ecology.

2.2.3 Loch Ness has an average water temperature range of 4.7°C in winter to 14.5°C in summer[7] and is a monomictic lake stratifying once per year typically from early summer through to the mid-late autumn (Smith et al., 1981[8], Wetzel 2001[9]). During the warmer months of the year, the water column thermally stratifies. During the colder winter/early spring months the water column is essentially isothermal, with sufficient thermal energy in the underlying water to prevent freezing aided by a strong internal wave known as an internal seiche (Thorpe, 1977[10]) and this is discussed further in Section 2.3. The breaking down of stratification later in the year is a result of colder air temperatures cooling surface waters resulting in convective mixing, as well as increased storminess that encourages deeper circulation.

2.2.4 In most large Scottish lochs stratification forms from around May until the autumn months. However, due to the larger volume of Loch Ness (including large heat inertia) both the onset and overturn of stratification is delayed, with isothermal conditions not beginning to return until around October or November (Jones & Young, 1998[11]). Stratification in Loch Ness is also considered to be less pronounced than in other lochs due to its volume (Maitland, 1981[12]) and potentially its high degree of exposure to wind induced mixing. The slower response to seasonal weather conditions may imply that Loch Ness would be more resistant to changes in water column structure that may occur as a result of the operation of a PSH scheme. The influence of a significant internal seiche may also contribute to weaker stratification, and this is discussed in the next section.

2.2.5 Although there is no recent data on the typical depths of the surface mixed layer in Loch Ness, there are numerous studies that report temperature profiles. Generally, the depth to the start of the thermocline is typically between 30 m and 50 m with spatial coherence over scales of 1 km or more (Watson, E.R., 1904[13]; Wedderburn & Watson, 1909[14]; Thorpe et al., 1972[15]; Thorpe, 1977; Thorpe & Hall, 1980[16]; Maitland, 1981; Jones et al., 1996[17];



Insert 1 Indicative Loch Ness thermal stratification depths.

[5] Wüest, A. and Lorke, A., 2003. Small-scale hydrodynamics in lakes. Annual Review of fluid mechanics, 35(1), pp.373-412.
[6] Boehrer, B. and Schultze, M., 2008. Stratification of lakes. Reviews of Geophysics, 46(2).
[7] Sea Temperature Info, 2024 Water temperature in Loch Ness today | United Kingdom
[8] Smith, B.D., Maitland, P.S., Young, M.R. and Carr, M.J., 1981. The littoral zoobenthos. In The Ecology of Scotland's Largest Lochs: Lomond, Awe, Ness, Morar and Shiel (pp. 155-203). Dordrecht: Springer Netherlands.
[9] Wetzel, R.G., 2001. Limnology: lake and river ecosystems. gulf professional publishing.
[10] Thorpe, S.A., 1977. Turbulence and mixing in a Scottish loch. Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences, 286(1334), pp.125-181.
[11] Jones, R.I. and Young, J.M., 1998. Control of bacterioplankton growth and abundance in deep, oligotrophic Loch Ness (Scotland). Aquatic microbial ecology, 15(1), pp.15-24.
[12] Maitland, P.S. 1981 ed., 2012. The ecology of Scotland's largest lochs: Lomond, Awe, Ness, Morar and Shiel (Vol. 44). Springer Science & Business Media.
[13] Watson, E.R., 1904. Movements of the waters of Loch Ness, as indicated by temperature observations. The Geographical Journal, 24(4), pp.430-437.
[14] Wedderburn, E.M. and Watson, W., 1909. XXXVIII.—Observations with a Current Meter in Loch Ness. Proceedings of the Royal Society of Edinburgh, 29, pp.619-647.
[15] Thorpe, S.A., Hall, A. and Crofts, I., 1972. The internal surge in Loch Ness. Nature, 237(5350), pp.96-98.
[16] Thorpe, S.A. and Hall, A.J., 1980. The mixing layer of Loch Ness. Journal of Fluid Mechanics, 101(4), pp.687-703.
[17] Jones, R.I., Young, J.M., Hartley, A.M. and Bailey-Watts, A.E., 1996. Light limitation of phytoplankton development in an oligotrophic lake-Loch Ness, Scotland. Freshwater Biology, 35(3), pp.533-543.

Jones et al., 1997[18]; and George & Winfield, 2000[19]). Changes in climate in recent decades may have altered this generalised structure, although even taking this into account the mixed layer in Loch Ness is expected to be relatively deep compared to other stratifying water bodies. A conceptual illustration of the water column structure of Loch Ness when stratified is provided in **Insert 1 Indicative Loch Ness thermal stratification depths** with a summary of existing data in **Table 2 Existing data on thermocline depth for Loch Ness**.

Table 2 Existing data on thermocline depth for Loch Ness

Source	Date	Location	Description
George, D.G. and Winfield, I.J. (2000) Factors influencing the spatial distribution of zooplankton and fish in Loch Ness, UK.	22nd/23rd July 1992	Northern end of loch between Urquhart Bay and Dores. Approx. NGR NH 55800 31100	Day-night phytoplankton, zooplankton and fish survey indicated a well-defined thermocline present at 35 m depth.
Jones, R.I., Laybourn-Parry, J., Walton, M.C. and Young, J.M. (1997) The forms and distribution of carbon in a deep, oligotrophic lake (Loch Ness, Scotland)	1991-1994	Fixed station 200 m depth (precise location not known)	Plankton distribution observed to correlate with temperature gradient: a layer beneath the epilimnion during summer stratification is identified at 40-50 m deep.
Jones, R.I., Young, J.M., Hartley, A.M. and Bailey-Watts, A.E. (1996) Light limitation of phytoplankton development in an oligotrophic lake-Loch Ness, Scotland.	Not known	Not known	States that even during summer stratification the morphometry of the loch and the strong prevailing winds produce a deep thermocline of about 30 m or greater.
Maitland, P.S. 1981 (ed. 2012) The ecology of Scotland's largest lochs: Lomond, Awe, Ness, Morar and Shiel	Not known	Not known	Quoting data from Smith et al,)1981) it is stated that no pronounced thermocline develops in Loch Ness. However, this does not mean that stratification does not occur, but it is weakly developed, and this may be less of an influence on water quality and biological processes, and the behaviour of aquatic organism.
Thorpe, S.A. and Hall, A.J. (1980) The mixing layer of Loch Ness.	1979	10 thermistors at 60 cm separation towed along loch from a boat	Upper 7 m surveyed only - recorded thermal gradient but above thermocline.
Thorpe, S.A. (1977) Turbulence and mixing in a Scottish loch	August to October 1973	Four points mid-loch between Foyers and Urquhart Bay	Refers to the epilimnion being around 43 m depth in September during strong winds but influenced by internal seiche.
Thorpe, S.A., Hall, A. and Crofts, I. (1972) The internal surge in Loch Ness	2nd – 3rd October 1971	Four moorings near western shore, between Foyers and Urquhart Bay	Focused on internal surge but a depth of 40 m for the thermocline is suggested.
Wedderburn, E.M. and Watson, W. (1909) Observations with a Current Meter in Loch Ness	August to September 1908	Buoys moored approx. 270 m off Invermoriston Pier, Fort Augustus and Glendoe Pier.	Sharply defined discontinuity described at 43 m deep.

2.2.6 Although often referred to as 'thermal' stratification, it is more appropriate to consider the difference in discrete layers of water in terms of the degree to which they are mixed. The epilimnion is generally considered to be a well-mixed layer of water, although this idealised concept may not be entirely homogeneous. Brainerd and Gregg (1995)[20] suggested that it may be better to sub-divide the mixed layer into two sub-regions: an actively mixed layer closer to the surface and a lower surface layer whose depth is determined by recent mixing and characterised by its homogeneity in terms of one or more variables, such as temperature or density. There are a

[18] Jones, R.I., Laybourn-Parry, J., Walton, M.C. and Young, J.M., 1997. The forms and distribution of carbon in a deep, oligotrophic lake (Loch Ness, Scotland). Internationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen, 26(2), pp.330-334.
[19] George, D.G. and Winfield, I.J., 2000. Factors influencing the spatial distribution of zooplankton and fish in Loch Ness, UK. Freshwater Biology, 43(4), pp.557-570.
[20] Brainerd, K.E. and Gregg, M.C., 1995. Surface mixed and mixing layer depths. Deep Sea Research Part I: Oceanographic Research Papers, 42(9), pp.1521-1543.

number of methods that are used to determine the mixed depth of the epilimnion, with temperature perhaps the most commonly used proxy. However, depending on which method is used to determine the mixed depth there can be different outcomes (Gray et al., 2020[21]). Ecologically important variables may also not be homogeneously distributed through the epilimnion.

2.3 Hydrodynamics

2.3.1 Although the different layers of water in a stratified lake are resistant to mixing, there are other mechanisms that can allow some circulation and mixing to occur and which apply to the whole volume of the lake. Mixing can occur when there is a sustained unidirectional wind that suddenly stops. The force of the wind causes water in the epilimnion to move to the downwind end of the lake increasing the depth of the epilimnion in that location and a corresponding decrease in the depth of the thermocline (see **Figure 2 Wind induced depression of thermocline (reproduced from George and Winfield, 2000)**). When the wind relents, the less dense water of the epilimnion moves back across the lake towards the upwind end. The hypolimnion also returns to its original position but can rock beyond its original position setting up a pendulum motion that may oscillate for hours or days after the wind has stopped. This rocking motion is known as an ‘internal seiche’ and can lead to mixing at the margins of the lake in a process known as entrainment.

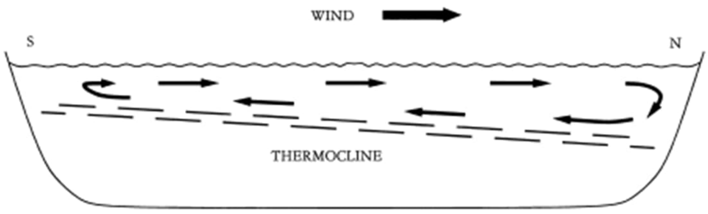


Figure 2 Wind induced depression of thermocline (reproduced from George and Winfield, 2000)

2.3.2 Although there are numerous rivers entering the loch, wind is considered by Thorpe (1977)[22] to be the dominant factor controlling patterns of internal circulation and Loch Ness is known to have a strong wind induced internal seiche (Thorpe, 1971[23], Thorpe et al; 1972[24]). The strong internal seiche is caused by the bathymetry of Loch Ness having a simple and trench-like regularity devoid of islands to disrupt flows (Loch Ness Project, 2024[25]), and because the loch is orientated northeast and southwest in line with the prevailing winds, which are also funnelled by hilly terrain either side (Thorpe, 1977[22]) (see **Figure 3 Loch Ness planform (reproduced from George and Winfield 2000) and simple loch long section (reproduced from Jones et al; 1997)**.). The strong internal seiche may be one of the reasons why stratification is relatively weak in Loch Ness and why the depth of the epilimnion is c. 30 m is relatively deep. If stratification in Loch Ness is weak it may have less of an influence on water quality, biological processes and the behaviour of aquatic organisms, than otherwise might be the case in water bodies with more pronounced stratification.

[21] Gray, E., Mackay, E.B., Elliott, J.A., Folkard, A.M. and Jones, I.D., 2020. Wide-spread inconsistency in estimation of lake mixed depth impacts interpretation of limnological processes. Water Research, 168, p.115136.
[22] Thorpe, S.A., 1977. Turbulence and mixing in a Scottish loch. Philosophical Transactions of the Royal Society of London. Series A, Mathematical and Physical Sciences, 286(1334), pp.125-181.
[23] Thorpe, S.A., 1971. Asymmetry of the internal seiche in Loch Ness. Nature, 231(5301), pp.306-308.
[24] Thorpe, S.A., Hall, A. and Crofts, I., 1972. The internal surge in Loch Ness. Nature, 237(5350), pp.96-98.
[25] Loch Ness Project, 2024. International Lake Environment Committee Foundation. *World Lake Database*.

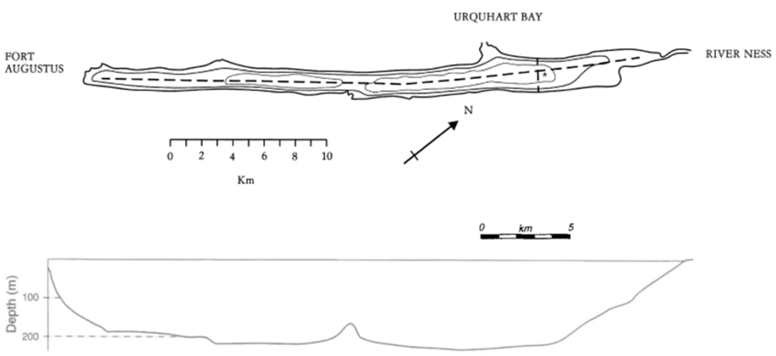


Figure 3 Loch Ness planform (reproduced from George and Winfield 2000) and simple loch long section (reproduced from Jones et al; 1997).

2.3.3 The internal seiche hardly affects the surface but the movement of millions of tons of water generates huge underwater waves on the thermocline over 40 m high and travelling around 1 km/h (Thorpe et al; 1972[24]). They are at their maximum during the autumn when the loch ceases to gain heat, and equinoctial gales keep the cooling epilimnion mixed to a uniform temperature. The difference in temperature between the epilimnion and the water beneath becomes less as the thermocline settles deeper but it is believed to be the spring before the whole loch is mixed to a uniform 5.5 °C (Pugh, D.T., 1977[26]). The high levels of mixing and internal seiche waves helps to prevent surface freezing in Loch Ness.

2.4 Water Quality

2.4.1 Loch Ness is a large, freshwater and oligotrophic (i.e. having relatively low levels of plant nutrients and high levels of dissolved oxygen) water body. It is designated under the Water Framework Directive (WFD) which is implemented through the Water Environment and Water Services (Scotland) Act 2003 (WEWS Act) as a distinct lake water body (ID 100156). According to the Scottish Environment Protection Agency (SEPA) on their online WFD Classification Hub, it is currently classified as being at Good Ecological Status and Good Chemical Status (2023, Cycle 3).

2.4.2 Jones et al. (1997)[27] discussed the twin threats of eutrophication and acidification on Loch Ness and attempted to examine the record of environmental change through an investigation of bed sediments. Although some nutrient enrichment was identified, it was insufficient to significantly alter water quality. Phosphorous is commonly the limiting nutrient in freshwater settings (Bennion, H., et al., 2024[28]) and currently the total phosphorus WFD status for Loch Ness is High (i.e. < 5µg/l), although it may in practice be borderline between Good and High, fluctuating due to natural conditions (SEPA, 2024[29]). SEPA phosphorus source apportionment modelling suggests that an estimated 39% of the phosphorus load comes from the upstream catchments (non-defined sources), 39% from sewage, fish farms, forestry and agricultural sources, with the remainder from urban runoff and natural land uses. The northern basin may be more nutrient rich than the southern basin, which may be attributed to greater arable farming in the northern basin's catchment (George and Winfield, 2000[30]). Acid neutralising capacity is also currently classified as High status under the WFD, although the very low alkalinity of its water means the water is vulnerable to acidic deposition.

2.4.3 Finally, allochthonous derived dissolved organic carbon has resulted in Loch Ness having moderately humic water (Bailey-Watts and Duncan, 1981[31]) and the unfavourable light conditions may limit the depth of the euphotic zone (George and Winfield, 2000[30]). Light availability may be the most significant control on phytoplankton growth rather than the very low nutrient levels (Jones et al., 1996[32]), for at least most of the year outside of the brighter

[26] Pugh, D.T., 1977. Geothermal gradients in British lake sediments. Limnology and Oceanography, 22(4), pp.581-596.
[27] Jones, V.J., Battarbee, R.W., Rose, N.L., Curtis, C., Appleby, P.G., Harriman, R. and Shine, A.J., 1997. Evidence for the pollution of Loch Ness from the analysis of its recent sediments. Science of the Total Environment, 203(1), pp.37-49.
[28] Bennion, H., Clarke, G., Frings, P., Goldsmith, B., Lait, J., Rose, N., Sime, I., Turner, S. and Yang, H., 2024. Paleolimnological evidence for variable impacts of fish farms on the water quality of Scottish freshwater lochs. Journal of Environmental Management, 369, p.122155.
[29] Scottish Environment Protection Agency (SEPA). 2024. Water Framework Directive Classifications – Loch Ness. Available Online: https://informatics.sepa.org.uk/WaterClassificationHub/
[30] George, D.G. and Winfield, I.J., 2000. Factors influencing the spatial distribution of zooplankton and fish in Loch Ness, UK. Freshwater Biology, 43(4), pp.557-570.
[31] Bailey-Watts, A.E. and Duncan, P., 1981. Chemical characterisation —A one-year comparative study. In The Ecology of Scotland's Largest Lochs: Lomond, Awe, Ness, Morar and Shiel (pp. 67-89). Dordrecht: Springer Netherlands.
[32] Jones, R.I., Young, J.M., Hartley, A.M. and Bailey-Watts, A.E., 1996. Light limitation of phytoplankton development in an oligotrophic lake-Loch Ness, Scotland. Freshwater Biology, 35(3), pp.533-543.

summer months. The depth of the mixed layer will also limit the growth of phytoplankton and circulation into deeper water carries them away from the euphotic zone.

2.5 Aquatic Ecology

Overview

2.5.1 A variety of organisms are found residing permanently or temporarily within Loch Ness, including plankton, fish, macrophyte and macroinvertebrate species. This review considers plankton only, as this is the group that is most likely to be affected by changes in stratification. Changes in plankton might then influence higher trophic levels. Further information on the baseline of fish and other aquatic ecological receptors can be found in **Chapter 9: Aquatic and Marine Ecology (Volume 2: Main Report)** and associated appendices.

Phytoplankton and Zooplankton

2.5.2 Plankton are free-floating small or microscopic organisms, which can be further divided into phytoplankton and zooplankton. Phytoplankton are autotrophic organisms (i.e. self-feeding) that are otherwise known as 'primary producers' and include photosynthesising bacteria (i.e. cyanobacteria) and single celled organisms such as diatoms. Zooplankton are heterotrophic organisms and may prey on phytoplankton and thus can play an important role in preventing harmful algal blooms from occurring. In turn, aquatic macroinvertebrates and fish are adapted to various ecological niches and may prey on plankton. The abundance and species composition of these groups of aquatic organisms are important for overall ecosystem health and water quality, and changes to one group can have repercussions for others.

2.5.3 Phytoplankton use photosynthesis to grow and thus are predominantly restricted to the euphotic zone (i.e. where light penetrates to a depth that equals around 1% of the light intensity at the surface). Light and nutrient availability (primarily nitrate, phosphate and silica), temperature and carbon dioxide are limiting factors controlling their growth. Under specific conditions phytoplankton and/or cyanobacteria can 'bloom' which can be aesthetically unpleasant and lead to water quality issues that are discussed separately below.

2.5.4 Phytoplankton is a WFD parameter monitored by SEPA and, according to data provided by them, is currently at High status in Loch Ness. The overall phytoplankton biomass expressed as chlorophyll-*a* in Loch Ness is relatively very low (<5 µg/l chlorophyll-*a*), with very low total biomass recorded (<1 mm^3/l). This is supported by Jones et al. (1996)[17] who report comparable mean values and a late summer maximum of less than 1.5 mg chlorophyll *a* m^{-3} in the upper 30 m of the water column (i.e. the approximate depth of the mixed epilimnion). In comparison, nutrient enriched water bodies in Scotland may have chlorophyll-*a* concentrations exceeding 40 µg/l chlorophyll-*a*, and total biomass including cyanobacteria between 5-10 mm^3/l.

2.5.5 One of the reasons for low phytoplankton biomass in Loch Ness may be a very low efficiency in converting available phosphorus (Bailey-Watts, 1998[33]). Phytoplankton development in Loch Ness may be constrained by light rather than by nutrients and thus is an exception to the general theory that phytoplankton growth in oligotrophic water bodies is constrained by nutrient availability, as shown in a study by Jones et al., 1996[34]. This study showed that chlorophyll-*a* content per unit of phytoplankton biovolume, and the maximum, light-saturated specific rate of photosynthesis, was comparable to other Scottish lochs, but that the efficiency to convert phosphorus into biomass was poor. Thus, they concluded that the very low phytoplankton biomass in Loch Ness was most likely controlled by unfavourable light conditions due to deep mixing and allochthonous derived dissolved organic carbon resulting in moderately humic water and unfavourable light conditions for phytoplankton growth.

2.5.6 The WFD phytoplankton classification includes a measure of cyanobacteria and from this the biomass is also considered by SEPA to be very low (<0.06 mm^3/l) with the dominant phytoplankton in terms of biomass being diatoms. There have been no substantiated pollution incidents including observations of blue-green algae (i.e. cyanobacteria) reported in Loch Ness since July 2022. SEPA data from before this date has been lost or compromised following a cyber-attack. Overall, although isolated instances may have occurred Loch Ness does not appear to have a history of frequent or regular harmful algal blooms as may be the case for some other more enriched Scottish lochs.

[33] Bailey-Watts, A.E., 1998. The phytoplankton ecology of the larger Scottish lochs. Botanical Journal of Scotland, 50(1), pp.63-92.
[34] Jones, R.I., Young, J.M., Hartley, A.M. and Bailey-Watts, A.E., 1996. Light limitation of phytoplankton development in an oligotrophic lake-Loch Ness, Scotland. Freshwater Biology, 35(3), pp.533-543.

2.5.7 The horizontal distribution of phytoplankton biomass in the deep, oligotrophic Loch Ness, has been investigated in various published studies, and is thought to be more dependent on wind-induced water circulation patterns than on differential growth of plankton in water masses of differing chemistry (Marti, C.L., et al., 2016[35]; Jones et al, 1995[36]; George, D.G. and Jones, D.H., 1987[37]). However, George and Winfield (2000)[38] observed greater concentrations of nitrate-nitrogen and phytoplankton chlorophyll-*a* in the northern basin than the southern basin, which they attributed to a greater proportion of arable land and thus nutrients in runoff. Thus, localised availability of nutrients may influence spatial distribution (Doering, P.H., et al, 1995), although light availability may control overall biomass volume.

2.5.8 Loch Ness hosts a zooplankton community mainly comprised of copepods (Maitland, 1981[39]). Like phytoplankton, zooplankton are mostly found in the top 20-30 m of the loch (George and Winfield, 2000[19]), where they feed on the former. Their spatial distribution, as weaker swimmers, is likely influenced by wind-induced water movements and the dispersion of allochthonous material from the main inflows (as a carbon source for bacterioplankton on which zooplankton will prey (Jones, R.I., et al., 2001[40])). In addition, no spatial correlation between total zooplankton and total fish abundance was observed, which may be because fish were actively foraging and thus were more abundant in areas where they had already been more active. Motile zooplankton species were also observed moving up and down through the water column allowing them to take advantage of different water chemistry and food availability, and to avoid predators in the different water layers. This phenomenon is known as ‘diel vertical migration’ and is likely triggered by relative changes in light intensity over a diurnal cycle, although presence of predators and avoidance of damage associated with ultraviolet light may also be factors (Meester, 2010[41]). Changes in water column characteristics can result in impacts on diel vertical migration pattern which may advantage or disadvantage different species.

2.5.9 Overall, populations of phytoplankton and zooplankton (and by extension fish) are likely to be found predominantly in the mixed zone due to light availability for photosynthesis, although transit into lower layers may be advantageous for certain species for a variety of reasons (e.g. motile zooplankton to evade predators). Populations are likely to be in equilibrium whereby new phytoplankton growth is efficiently consumed by zooplankton and so on, as indicated by stable bacterial densities (Jones and Young, 1998[42]). Perturbation of the ecosystem could result in changes, and these changes could lead to unforeseen secondary effects.

[35] Marti, C.L., Imberger, J., Garibaldi, L. and Leoni, B., 2016. Using time scales to characterise phytoplankton assemblages in a deep subalpine lake during the thermal stratification period: Lake Iseo, Italy. Water Resources Research, 52(3), pp.1762-1780.
[36] Jones, R.I., Fulcher, A.S., Jayakody, J.K.U., LAYBOURN-PARRY, J., Shine, A.J., Walton, M.C. and Young, J.M., 1995. The horizontal distribution of plankton in a deep, oligotrophic lake—Loch Ness, Scotland. Freshwater Biology, 33(2), pp.161-170.
[37] George, D.G. and Jones, D.H., 1987. Catchment effects on the horizontal distribution of phytoplankton in five of Scotland's largest freshwater lochs. The Journal of Ecology, pp.43-59.
[38] George, D.G. and Winfield, I.J., 2000. Factors influencing the spatial distribution of zooplankton and fish in Loch Ness, UK. Freshwater Biology, 43(4), pp.557-570.
[39] Maitland, P.S. 1981 ed., 2012. The ecology of Scotland’s largest lochs: Lomond, Awe, Ness, Morar and Shiel (Vol. 44). Springer Science & Business Media.
[40] Jones, R.I., Grey, J., Quarmby, C. and Sleep, D., 2001. Sources and fluxes of inorganic carbon in a deep, oligotrophic lake (Loch Ness, Scotland). Global Biogeochemical Cycles, 15(4), pp.863-870.
[41] Meester, L.D., 2010. Diel vertical migration. Plankton of inland waters, pp.651-658.
[42] Jones, R.I. and Young, J.M., 1998. Control of bacterioplankton growth and abundance in deep, oligotrophic Loch Ness (Scotland). Aquatic microbial ecology, 15(1), pp.15-24.

3 Potential Impacts

3.1 Limnological Effects of Stratification

3.1.1 Temperature has a significant influence on chemical and biological reactions, and during stratification strong temperature gradients (i.e. the thermocline) can significantly limit the diffusion of dissolved oxygen from the water's surface to the bottom of the water body (Hamze-Ziabari, S.M., et al., 2022[43]). There is also reduced mixing by convection and advection currents between the epilimnion and the hypolimnion. Over time, respiration by aquatic organisms and the aerobic decomposition of organic matter progressively uses up the available dissolved oxygen in the hypolimnion, which is not replaced. In addition to the anoxic conditions that develop at depth, stratification can lead to the build-up of ammonia in the hypolimnion that can be toxic to aquatic organisms; the release of sediment-derived bioavailable phosphorus and / or nitrogen; and the reduction of metals in bottom sediments into more soluble, and potentially toxic forms, such as the formation of methylmercury. Thus, after a period of stratification the water quality in the hypolimnion is expected to be significantly poorer than in the overlying epilimnion. At the same time, under stratification there is less dilution and dispersion available in the epilimnion of catchment derived chemical compounds and nutrients, which can also increase the risk of algal blooms occurring, although the causal factors are complex and varied, and it is noted that Loch Ness does not have a history of algal blooms, is oligotrophic and has a very low chlorophyll-*a* levels.

3.1.2 Although there can be intermittent periods of entrainment of hypolimnion water into the epilimnion during a period of stratification (such as from a wind induced internal seiche), at some point in the autumn, the combination of evaporation, air cooling and wind induced mixing of the surface water (Jenkin, P.M., 1942[44]) results in destabilisation of the distinct water layers and mixing of the whole water body until the next summer (i.e. the mixolimnion). This effectively mixes the poorer quality water of the hypolimnion that is now low in dissolved oxygen but nutrient rich in bioavailable phosphorous with the epilimnion. The quality of water in the hypolimnion will depend on many factors such as the duration of stratification and supply of dead organic matter. The impact on overall water quality in the whole water body will be controlled by the quality of the water in the distinctive layers, the ratio of volumes and how rapidly mixing progresses. The sudden release of nutrients could encourage the growth of phytoplankton and potentially result in algal blooms (Crockford et al, 2015[45]), providing other factors such as light availability and temperature are conducive, and providing there is not a sufficiently high degree of predation by zooplankton. Where a bloom does not occur, there is still the potential that higher levels of nutrients persist that 'prime' the loch for early spring blooms the following year. However, overturn does re-oxygenate bottom waters reducing the release of sediment-derived phosphorus and permitting its precipitation (i.e. $FePO_4$) as well as carrying algal mass from the epilimnion to lower depths beyond the euphotic zone where photosynthesis is not possible. Understanding the balance of these various factors is complex and difficult and ultimately would require computational modelling to investigate (Castrillo, M. et al, 2024[46]).

3.2 Limnological Effects of PSH - Introduction

3.2.1 PSH systems are a means of generating electricity at times of higher demand and storing excess electricity when there is lower demand. At times of surplus electricity generation, water is pumped from one water body at a lower elevation – the 'tailpond' – into a reservoir at a higher elevation – the 'headpond'. Thus, energy is stored in the headpond as potential energy. When there is a greater demand for electricity, the water is released down through a tunnel or pipe back into the tailpond, passing through turbines that convert this potential energy into electricity. This section considers the types of impacts that the operation of a PSH project can have on stratification of deep lakes, and what this might mean for water quality, biological processes and the behaviour of aquatic organisms.

3.2.2 Although generally considered a power generating technology of low environmental impact, the discharge of water can encourage mixing that has been found to delay, weaken or even eliminate stratification resulting in changes in water chemistry, which in turn can affect biological processes and aquatic organisms (in terms of

[43] Hamze-Ziabari, S.M., Lemmin, U., Soulignac, F., Foroughan, M. and Barry, D.A., 2022. Basin-scale gyres and mesoscale eddies in large lakes: A novel procedure for their detection and characterisation, assessed in Lake Geneva. Geoscientific Model Development, 15(23), pp.8785-8807.
[44] Jenkin, P.M., 1942. Seasonal changes in the temperature of Windermere (English Lake District). The Journal of Animal Ecology, pp.248-269.
[45] Crockford, L., Jordan, P., Melland, A.R. and Taylor, D., 2015. Storm-triggered, increased supply of sediment-derived phosphorus to the epilimnion in a small freshwater lake. Inland Waters, 5(1), pp.15-26.
[46] Castrillo, M., Aguilar, F. and García-Díaz, D., 2024. A data-driven approach for the assessment of the thermal stratification of reservoirs based on readily available data. Ecological Informatics, 82, p.102672.

abundance, composition and behaviour) (e.g. Tippett, 1978[47]; Imboden, 1980[48]; Potter, 1982[49]; and US Bureau of Reclamation, 1993[50]).

3.2.3 Imboden (1980)[48] stated that the operation of a PSH project can affect water temperature in the tailpond that could alter biological growth rates, respiration and mineralisation reactions, change algal populations due to new environmental conditions, especially temperature and turbulence (e.g. some species are more sensitive to turbulent vertical displacement than others), which could lead to indirect effects on zooplankton (and subsequently on fish populations).

3.2.4 Kobler et al. (2018)[51] categorised impacts as abiotic (i.e. physical, geochemical etc.) and biotic (i.e. ecological). Abiotic effects include changes in water temperature, stratification, water level fluctuations, sediment resuspension, oxygen and nutrient cycling in the water column, as well as modifications of inorganic suspended sediment, which can affect turbidity and therefore light penetration thus photosynthesis by phytoplankton (Bonalumi et al., 2011[52]). Additionally, lake-internal circulation patterns can carry phytoplankton into deeper water beyond the euphotic zone where they cannot photosynthesise and grow. The same water movements can carry more oxygen rich water to deeper layers beneath the thermocline which can alter chemical processes in that hypolimnion.

3.2.5 The operation of a PSH project can result in changes to stratification and this can result in numerous, complex and interrelated impacts to water quality, biological processes and aquatic organisms. There have been only a limited number of direct studies of these impacts and their causal mechanisms and inter-relationships are not well understood. The remainder of this section provides further information on what is known and how it may apply to the Proposed Development. However, careful interpretation of the results of each study is required due to the large number of variables (e.g., different geographical settings, lake characteristics, operational modes of different PSH schemes etc.).

3.3 Potential Changes in Stratification

3.3.1 The discharge from a PSH project may create turbulence and induce mixing upon entry into the tailpond. Where the tailpond is not stratified, the induced mixing may discourage stratification from forming. If stratified and the discharge is within the mixed epilimnion, the increased mixing may encourage a deepening of the thermocline and a deeper mixed surface layer. By contrast, if the discharge was at a lower depth, it may encourage additional mixing between the discrete layers of water and weaken stratification (Yang, S. et al., 2023[53]). Assessing the Cruachan 1 pumped-storage hydro scheme shortly after opening, Tippett (1978)[47] identified that the increased mixing of the upper water column in Loch Awe had the effect of delaying the onset of stratification, sharpening, and deepening the thermocline (at least during the early part of the summer before more intense solar radiation later in the summer compensated for the impact). At the point of discharge, Loch Awe has a maximum water depth of around 75 m and the mixed surface layer is c. 10-15 m deep. Based on these observations, three broad outcomes may occur and these are shown conceptually in **Figure 4 Potential outcomes to thermal stratification close to the Tailpond inlet / outlet during operation of the Development**, with the likelihood of occurrence increasing closer to the outlet and with more frequent operation of the PSH plant.

[47] Tippett, R., 1978. Effect of a pump-storage hydro-electric scheme on the stratification and ecology of a Scottish loch: With 3 figures in the text. Internationale Vereinigung für theoretische und angewandte Limnologie: Verhandlungen, 20(4), pp.2697-2700.
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[49] Potter, D.U., Stevens, M.P. and Meyer, J.L., 1982. Changes in physical and chemical variables in a new reservoir due to pumped storage operations 1. JAWRA Journal of the American Water Resources Association, 18(4), pp.627-633.
[50] US Bureau of Reclamation, 1993. Water supply conditions for the Western states. Bureau of Reclamation, pp. 44
[51] Kobler, U.G., Wüest, A. and Schmid, M., 2018. Effects of lake–reservoir pumped-storage operations on temperature and water quality. Sustainability, 10(6), p.1968.
[52] Bonalumi, M., Anselmetti, F.S., Kaegi, R. and Wüest, A., 2011. Particle dynamics in high-Alpine proglacial reservoirs modified by pumped-storage operation. Water Resources Research, 47(9).
[53] Yang, S., Zhang, Z., Ji, Q., Liang, R. and Li, K., 2023. Study on the water temperature distribution characteristics of a mixed pumped storage power station reservoir: A case study of Jinshuitan Reservoir. Renewable Energy, 202, pp.1012-1020.

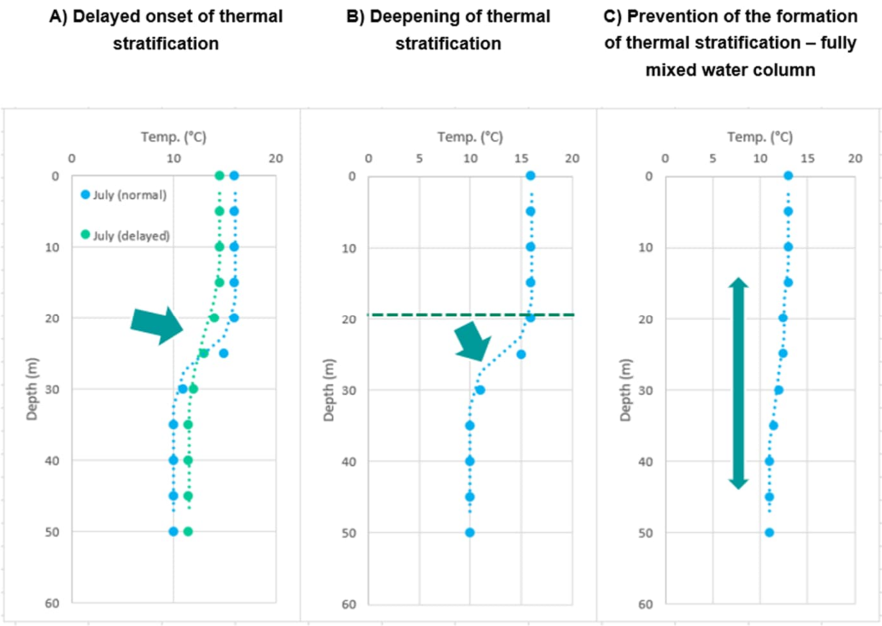

Figure 4 Potential outcomes to thermal stratification close to the Tailpond inlet / outlet during operation of the Development

3.3.2 Although there is a focus on the discharge, the potential impact of abstraction from the tailpond during pumping cannot be entirely ignored, and there is evidence from numerous conventional hydropower projects and some PSH schemes that abstraction from deep water can also affect the characteristics of the water column during periods of stratification (e.g. Duka et al., 2021[54], Ibarra et al., 2015[55], Bermudez, 2018[56], Kobler et al., 2018[57]). However, providing the abstraction and discharge point remains at the same depth, which for the Proposed Development it will be, the risk of mixing water of potentially different quality is reduced. Overall, many factors are important to determine the potential for discharge (and abstraction) induced mixing such as the velocity, volume, duration and frequency of the discharge (or abstraction), but also its temperature and density compared to the water in the tailpond. Buoyancy forces are also important and tend to mean that any inflow remains at the depth at which it becomes naturally buoyant rather than dispersing and being diluted in the water body as a whole (Marti et al., 2011[58]). If this is within the euphotic zone or is nutrient rich it may encourage the growth of phytoplankton at that depth. Thus, the quality of the water (e.g. nutrients and turbidity) is also important for understanding the potential impacts of the discharge, and these are discussed later under 'Water Quality and Biological Impacts' although reference is made to these potential impacts throughout the remainder of this section.

3.3.3 Hydrodynamic disruption of stratification or the impact of a discharge when the tailpond is mixed, may result in adverse water quality and ecological impacts. However, although a natural process, stratification and the mixing after a period of stratification can also be associated with episodes of poorer water quality that could promote algal growth (Nowlin et al., 2008[59]) and potentially lead to harmful algal blooms occurring under certain conditions. Thus, water quality impacts from changes to stratification may not necessarily be negative. For example, when investigating a new PSH scheme on Lake Oconee, Georgia (USA), Potter et al. (1982)[60] found that the operation of the PSH project weakened the stratification of the lake but that the more homogeneous vertical profiles were generally higher in oxygen and lower in dissolved nutrient concentrations compared to the pre-development baseline, where temperature, oxygen, pH, inorganic nitrogen, and phosphorus were vertically stratified with severe hypolimnetic oxygen depletion. Indeed, preventing stratification is one method that can be applied to

[54] Duka, M.A., Shintani, T. and Yokoyama, K., 2021. Thermal stratification responses of a monomictic reservoir under different seasons and operation schemes. Science of the Total Environment, 767, p.144423.
[55] Ibarra, G., De la Fuente, A. and Contreras, M., 2015. Effects of hydropeaking on the hydrodynamics of a stratified reservoir: the Rapel Reservoir case study. Journal of Hydraulic Research, 53(6), pp.760-772.
[56] Bermúdez, M., Cea, L., Puertas, J., Rodríguez, N. and Baztán, J., 2018. Numerical modelling of the impact of a pumped-storage hydroelectric power plant on the reservoirs' thermal stratification structure: a case study in NW Spain. Environmental Modeling & Assessment, 23, pp.71-85.
[57] Kobler, U.G., Wüest, A. and Schmid, M., 2018. Effects of lake–reservoir pumped-storage operations on temperature and water quality. Sustainability, 10(6), p.1968.
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[59] Nowlin, W.H., Vanni, M.J. and Yang, L.H., 2008. Comparing resource pulses in aquatic and terrestrial ecosystems. Ecology, 89(3), pp.647-659.
[60] Potter, D.U., Stevens, M.P. and Meyer, J.L., 1982. Changes in physical and chemical variables in a new reservoir due to pumped storage operations 1. JAWRA Journal of the American Water Resources Association, 18(4), pp.627-633.

control algal blooms where internal recycling of nutrients is a primary factor (Toffolon et al., 2013[61]). Preventing stratification reduces the release of sediment-derived nutrients under anoxic bottom water conditions and increases the mixing depth of nuisance blue-green algae, removing them from the euphotic zone to darker depths where they cannot photosynthesise. In some central European Lakes, recent action to reduce catchment nutrient loads coupled with climate change that has prevented overturn, has resulted in nutrients being consumed in the epilimnion to the detriment of maintaining a healthy ecosystem (Yankova et al., 2017[62]).

3.3.4 Observing a PSH on Lake Ivoe in Sweden, Bengtsson (1979)[63] showed that where the discharge from the PSH scheme is carefully controlled to rapidly dissipate the kinetic energy of the outflowing water, there may be a negligible impact on the summer stratification, as well as autumn overturn. In this case, the summer thermocline was observed at 15 m depth with the discharge disrupting the upper 10 m of the lake only. It is not known what the operating regime of the PSH was, and it is noted that as the thermocline forms in the early summer it may be above 10 m and thus there could be some localised and short-term impacts similar to what Tippett (1978)[47] observed on Loch Awe. However, this nonetheless shows that impacts may be minimised through careful control of the discharge. The relative size of the discharge, its duration, velocity and frequency will be important factors, and the spatial extent of the influence of the discharge is not reported by Tippett (1978) [47] or Bengtsson (1979) [63]. Bengtsson (1979)[63] also suggests that increased turbidity might alter the absorption of sunlight which could reduce natural warming, although a new equilibrium would be reached after a short period of time.

3.3.5 Anderson (2010)[64] also concluded that the impacts of PSH projects on lake stratification are strongly dependent upon design and operational features of the development, and that hydrodynamic modelling can support designs that minimise environmental impacts on water quality and the aquatic ecosystem. This was based on the outcome of a hydrodynamic modelling study that concluded that significant adverse impacts from the operation of a PSH plant would not occur on Lake Elsinore (a shallow, polymictic lake in southern California, USA), due to the large intake cross-section (in this case 1,200 m^2) and shore-mounted design that limits turbulent kinetic energy input into the lake relative to other pumped-storage systems.

3.3.6 Another study by Bermudez (2018)[65] looked at how PSH schemes would impact stratification within two large reservoirs in Galicia, northwest Spain. A 3D hydrodynamic model was used to investigate the impact of the existing PSH projects operation on thermal structure, deep-water mixing and water column characteristics. In both reservoirs, a degradation of the thermocline was observed in the vicinity of abstracting/discharge structures. It was suggested that it is not just the energy and depths of the discharge that is important, but also that the geometry of the intake-outlet structures and the morphological characteristics of the tailpond. When assessing the discharge, a high level of mixing was observed in the vicinity of outfalls to both reservoirs, but in one the impact was localised and in the other the impact was more significant and resulted in the breaking down of stratification over a relatively wide area. The difference in impacts was attributed to lake morphology, with the more impacted reservoir being longer and narrower, which seemed to encourage mixing over a larger spatial area. However, it should be noted that mean and max depths of the two reservoirs in this study were c. 12 m / 6 m and 30 m/ 20 m and thus are considerably shallower than Loch Ness.

3.3.7 Bermudez (2018)[66] also identified the importance of discharge temperature and nutrient loads on the receiving water body. If the depth of abstraction from the headpond is different to the depth of discharge into the tailpond, so that water is abstracted from the headpond hypolimnion and discharged to the tailpond epilimnion (or vice versa), the water discharged during generation may be of a different quality to that in the tailpond by virtue of changes that have occurred in the headpond after abstraction from the tailpond. This would be more significant if the headpond itself stratifies or if water is held for long periods without operation. There may also be some catchment influences, although this is not expected to be significantly different for the Proposed Development given the proximity of the proposed Headpond to Loch Ness and both being in the same overall catchment. However, there may be practical engineering reasons why water from a headpond has to be abstracted at a lower depth and discharged into an associated tailpond at a higher water level.

[61] Toffolon, M., Ragazzi, M., Righetti, M., Teodoru, C.R., Tubino, M., Defrancesco, C. and Pozzi, S., 2013. Effects of artificial hypolimnetic oxygenation in a shallow lake. Part 1: Phenomenological description and management. Journal of environmental management, 114, pp.520-529.
[62] Yankova, Y., Neuenschwander, S., Köster, O. and Posch, T., 2017. Abrupt stop of deep water turnover with lake warming: Drastic consequences for algal primary producers. Scientific Reports, 7(1), p.13770.
[63] Bengtsson, L., 1979. Influence of a proposed pumped storage hydro-power plant on the thermal stratification of Lake Ivoe, Sweden.
[64] Anderson, M.A., 2010. Influence of pumped-storage hydroelectric plant operation on a shallow polymictic lake: Predictions from 3-D hydrodynamic modelling. Lake and Reservoir Management, 26(1), pp.1-13.
[65] Bermúdez, M., Cea, L., Puertas, J., Rodríguez, N. and Baztán, J., 2018. Numerical modelling of the impact of a pumped-storage hydroelectric power plant on the reservoirs' thermal stratification structure: a case study in NW Spain. Environmental Modeling & Assessment, 23, pp.71-85.

3.3.8 Some studies have been conducted on PSH schemes using mountainous Swiss lakes as tailponds and which focused on the impacts on stratification. Bonalumi et al. (2011)[66] presented a study on pumped storage works connecting two reservoirs in the Grimsel region of Switzerland, with different particle concentrations and temperatures noted for each. With the operation of the PSH scheme the upper reservoir is found to be warmer and more thermally stratified following the ice break-up in spring, with the pumped-storage operations modifying these factors in both the headpond (Oberaasee) and tailpond (Grimselsee). Water was found to be more turbid and a slightly higher temperature at the inlet/outlet point than in the centre of the lake when measured at varying depths. Whilst this study does indicate that PSH schemes can alter the temperature gradient within a temperate lake, it is limited in its relevance to Loch Ness as Grimselsee is smaller, cooled by glacial runoff and has a thermocline only about 5 m deep. The high particle concentration derived from glacial meltwater is a key consideration in this example, with the basin with higher particle loads not warming as fast or stratifying. However, the operation of the PSH tends to equalises the particle size concentrations in the Headpond and Tailpond, particularly during the winter when there is less meltwater passing through the system. As Loch Ness has a relatively low total suspended sediment and turbidity level, and the Headpond will be located nearby and in the same catchment, it is not expected that there would be a significant difference in suspended sediment concentrations and turbidity.

3.3.9 Bonalumi et al. (2012)[67] later used hydrodynamic modelling to simulate the long term (over 27 years) impact on two basins in Switzerland of four different hydrological conditions both with and without pumped storage systems. It showed that the full operation of a proposed PSH scheme (worst case) led to the transfer of heat between the two basins with an increase in temperature in the hypolimnion in both for most of the year, with the increase being most pronounced in the upper hypolimnion of the tailpond towards the end of the summer. It was concluded that this temperature increase was partially due to frictional losses in the penstocks, pumps and turbines and warming from intense coupling to the atmosphere while water resides in the shallower upper reservoir. These impacts were most pronounced during warm and dry years, when the upper reservoir, which is shallower and more exposed to meteorological conditions, was more strongly heated, and where the effects were offset less by strong hydrological flows through the system. Interestingly, in warm and dry years when the hypolimnion in the headpond in this case was more intensely warmed, the corresponding strong stratification in the tailpond reduced heat flux into the tailpond hypolimnion, thus accentuating the change in temperature as a result of the PSH schemes operation. The inlet and outlets to and from the headpond and tailpond in this PSH system were into the hypolimnion, as opposed to the epilimnion as will be the case for the Proposed Development. Thus, the greater atmosphere coupling of colder hypolimnion water in the headpond than in the tailpond, together with reduced downwards heat flux in the tailpond during periods of string stratification, may not be so important for the Proposed Development.

3.3.10 In this scenario, the headpond Lago Bianco (reservoir) has a surface area of 1.43 km^2, a maximum depth of 26 m and a volume of 29 Mm^3, which is not too dissimilar to the proposed Headpond in the Proposed Development, although it is at a much higher altitude than the associated tailpond (c. 1300 m higher) where average air temperatures are around 5°C cooler and wind speeds stronger. Lago Bianco is also ice cover during the winter and receives high concentrations of fine sediment from glacial meltwater. The tailpond in this study is the natural Lago di Poschiaro, which is much smaller than Loch Ness, with a surface area of only 1.95 km^2, a maximum depth of 85 m and a volume of 111 x 10^6 m^3. This is around four times the size of the headpond and compared to Loch Ness that as a surface area of 56.4 km^2, c. 230 m maximum depth and holds around 7,452 Mm^3 and which is c. 250 times larger than the Headpond for the Proposed Development. It is also dimictic as opposed to monomictic, being inversely stratified over winter and spring and may have a thin cover of ice if a cold winter.

3.3.11 The modelling done by Bonalumi et al. (2012)[68] highlights the potential for 'year on year' variation in impact from the operation of a PSH scheme, and indeed the range of model outcomes discussed in this paper reflects on the impact of particular weather patterns and events on stratification at any given time. The bathymetry (volume and depth) of the headpond, but also the operating regime, are therefore important considerations. The modelling also showed a small lengthening of the period of stratification in the tailpond as a result of it forming earlier in the year. This is likely because the surface waters for the tailpond are warmed more quickly under operation of the PSH scheme. This is contrary to older empirical studies that observed delayed or reduced stratification. In these cases, stronger solar radiation was required to overcome the increased water column mixing caused by the operation of a PSH plant. Overall, whilst there are some similarities to Loch Ness in terms of geography and climate, there are also notable differences such as the freezing of lake surfaces, shallower depths and volumes, inlet/outlet into the hypolimnion as opposed to the epilimnion, much greater elevation difference, and different relative sizes of the

[66] Bonalumi, M., Anselmetti, F.S., Kaegi, R. and Wüest, A., 2011. Particle dynamics in high-Alpine proglacial reservoirs modified by pumped-storage operation. Water Resources Research, 47(9).
[67] Bonalumi, M., Anselmetti, F.S., Wüest, A. and Schmid, M., 2012. Modeling of temperature and turbidity in a natural lake and a reservoir connected by pumped-storage operations. Water Resources Research, 48(8).

headpond and tailpond that limit the application of these outcomes to the case being assessed for Loch Ness. Therefore, the applications of the conclusions of this study to the Proposed Development should be treated with some care.

3.3.12 Kobler et al. (2018)[68] carried out a hydrodynamic modelling study to assess the impacts on temperature, stratification, and water quality in a natural lake and a reservoir in Switzerland from the Etzelwerk PSH scheme that would be renewed. The Sihlsee Reservoir is the headpond and Upper Lake Zurich the tailpond, with maximum water depths at highest water level of 23 m and 48 m, respectively. Both lakes stratify in the summer and develop suboxic or anoxic conditions in the hypolimnion. The study considered scenarios that would help evaluate the relative impact of the exchange of water between the two water bodies and the depth of water removal from the headpond. This study is useful in that it allows inferences to be made as to the merits of abstraction and discharge from and to either the epilimnion or hypolimnion. However, the results are complicated by the fact there is an existing PSH scheme in operation and are focused on the headpond reservoir, which is not a concern for the Proposed Development. It highlights that mixing of water of different chemistries or temperatures will naturally lead to changes in both water bodies, with the smaller water body likely to experience the greatest change. The effects on Upper Lake Zurich were much less pronounced due to its larger volume and higher natural discharges. Although local effects of PSH operation in the vicinity of the intake/outlet on Upper Lake Zurich were expected, investigation of this was beyond the scope of the modelling tools used. As the difference in size of the headpond and tailpond in this study is more similar to the Proposed Development, the outcomes for Upper Lake Zurich may be more comparable as to those likely in Loch Ness.

3.3.13 **Table 3 Summary of studies investigating impacts on thermal stratification from PSH scheme** provides a summary of the studies which have been described above and that have investigated the impact of existing or proposed PSH schemes on lake stratification, either through monitoring or hydrodynamic modelling.

Table 3 Summary of studies investigating impacts on thermal stratification from PSH scheme

Source	Tailpond	Outcome	Relevance to Loch Ness
Tippett (1978)	Loch Awe, Scotland, UK	Monitored the impact on thermal stratification in Loch Awe from the operation of the Cruachan 1 PSH scheme. Increased mixing of the upper water column had the effect of delaying the onset of stratification, sharpening and deepening the thermocline, at least during the early part of the summer before more intense solar radiation compensated for the impact.	Loch Awe is a large, deep-water body, but it is smaller in surface areas and significantly shallower (c. 38.5 km^2 and maximum depth c. 94 m) than Loch Ness. The depth of the mixed zone is also shallower being <20m deep. Located in Scotland so geographically and climatically similar characteristics to Loch Ness, but more nutrient enriched and with a history of harmful algal blooms (HAB). Limited information is available on the PSH scheme.
Bengtsson (1979)	Lake Ivoe, Sweden	Observations of an existing PSH scheme reported a negligible impact on the summer stratification, as well as autumn breakdown. In this case, the summer thermocline was observed at 15 m depth with the discharge disrupting the upper 10 m of the lake only. The reason was attributed to controlling the energy from the discharge so that it is rapidly dissipated.	Large water body with a surface area of c. 55 km^2 and a maximum depth of c. 50 m, but still considerably shallower than Loch Ness. The depth of the mixed layer is also much shallower than in Loch Ness. Located in Sweden so climate broadly comparable to Loch Ness, but colder on average and greater potential for freezing over in the winter. Limited information is available on the PSH scheme.
Imboden (1980)	Idealised lake, Switzerland	A mathematical model developed by Imboden (1980) indicated that pumped-storage operation delayed onset of stratification by almost 2 months in an idealised Swiss lake.	Modelled lake with a proposed surface area of 30 km^2 and maximum depth of 200 m, which is more comparable to Loch Ness. Outlet modelled at 4 to 15 m deep, which is also similar to the Proposed Development, although not known what the cross-sectional area is. Based on Lake Lucerne in Switzerland so broadly similar climate to Loch Ness, but mountainous region that may be more affected by glacial melt water that can have elevated turbidity.
Calhoun et al. (1980)	Idealised 'run of the river' reservoir system, Virginia, USA	Model simulations of an idealised 'run of the river' reservoir system operated as a pumped-storage system in Virginia demonstrated deepening of the mixed layer in both	Modelled reservoir based on the then proposed Blue Ridge PSH project in Virginia, USA. Proposed lower reservoir had 50 km^2 surface area. Different climate and geography from Loch Ness. Unknown outlet

[68] Kobler, U.G., Wüest, A. and Schmid, M., 2018. Effects of lake–reservoir pumped-storage operations on temperature and water quality. Sustainability, 10(6), p.1968.

Source	Tailpond	Outcome	Relevance to Loch Ness
		the upper and lower reservoirs by up to 20 m and lowered temperatures by about 1–3°C.	design as project was cancelled before this stage.
Potter et al. (1982)	Lake Oconee, Georgia, USA	Pumped-storage operation at Lake Oconee eliminated strong summer stratification in Lake Oconee.	Large surface (c. 77 km^2) but relatively shallow (maximum depth c. 20 m) water body in Georgia, USA, so significantly shallower than Loch Ness. Poor stratification and thermocline data recorded due to shallow water. Different climate to Loch Ness.
Anderson (2010)	Lake Elsinore, a shallow, polymictic lake in southern California, USA	Hydrodynamic modelling predicted no significant impacts which was attributed to the large intake cross-section (in this case 1,200 m^2) and shore-mounted design that limits turbulent kinetic energy input into the lake relative to other pumped-storage systems.	Comparatively small water body in California, USA with surface area of just c. 12 km^2 and a maximum depth c. 13 m. Mixed layer modelled at < 8 m depth. Very different climate to Loch Ness. Inlet/outlet structure modelled at shoreline with diameter of 12.8 m by 150 m, which is comparable to the Proposed Development, although depth and size of the tailpond considerably smaller. Elevation difference to upper reservoir is 380 m, which is similar to the Proposed Development (>400 m).
Bonalumi et al. (2011)	Lake Oberaasee (headpond) and Lake Grimselsee (tailpond), Switzerland	With the operation of the PSH scheme the upper reservoir is found to be warmer and more thermally stratified following the ice break-up in spring, with the pumped-storage operations modifying these factors in both the headpond (Oberaasee) and tailpond (Grimselsee). High levels of particulates from glacial meltwater were a critical factor affecting the outcome.	Small Swiss lake (Grimselsee). Very small surface area of just 2.63 km^2 but relatively very deep (maximum depth c. 100 m). Very shallow thermocline in upper few meters. Montane climate similar to Loch Ness but higher elevation with influence of glacial runoff that may contain higher suspended sediment concentrations. The headpond was also ice covered in the winter, and the tailpond inversely stratified (i.e. dimictic rather than monomictic). Therefore, not a direct comparison.
Bonalumi et al. (2012)	Lago Bianco (headpond) and Lago di Poschiaro (tailpond), Switzerland	Operation of the proposed PSH led to an increase in temperature in both basins for most of the year, with the increase being most pronounced (up to 4°C) in the upper hypolimnion of the tailpond towards the end of the summer. It was concluded that this temperature increase was partially due to frictional losses in the penstocks, pumps and turbines (almost 50%), with the remainder of the warming from intense coupling to the atmosphere while water resides in the shallower upper reservoir.	Tailpond is a small Swiss lake (Poschiaro) with a surface area of c. 1.95 km^2 but relatively deep at a maximum of c. 85 m. Thermocline depth uncertain. Montane climate similar to Loch Ness but higher elevation and elevation difference between headpond and tailpond (c. 1300 m), with influence of glacial runoff that may contain higher concentrations of suspended sediment. The headpond is also ice covered in the winter, and the tailpond sometimes, The tailpond is dimictic rather than monomictic like Loch Ness that does not freeze in winter. Outlets modelled at depths of 28, 38 and 58 m, so into deeper water (hypolimnion) than the Proposed Development (inlet/outlets to the epilimnion). Therefore, not a direct comparison.
Bermudez (2018)	Salas and Conchas reservoirs, Galicia, NW Spain	A 3D hydrodynamic model was used to investigate the impact of the PSH plants operation on thermal structure, deep water mixing and water column characteristics of two large reservoirs. In both reservoirs, a degradation of the thermocline was observed in the vicinity of abstracting structures. However, wider spatial impacts were restricted to one reservoir, which was attributed to its longer and narrower morphology, which seemed to encourage mixing over a larger spatial area.	Small Spanish reservoir (As Conchas). Surface area c. 6.3 km^2 and maximum depth c. 30 m. Thermocline depth uncertain. Different climate to Loch Ness. Outlets modelled at 15 and 30 m depths, so one comparable to the Proposed Development.
Kobler et al. (2018)	Lake Sihlsee (headpond) Upper Lake Zurich (tailpond)	Highlights that mixing of water of different chemistries or temperatures will naturally lead to changes in both water bodies, with	A large Swiss lake (Upper Lake Zurich) with a surface area c. 88.6 km^2 and maximum depth c. 48 m. Mixed layer depth around 12 to 14 m, so much shallower than Loch

Source	Tailpond	Outcome	Relevance to Loch Ness
		the smaller water body likely to experience the greatest change. The relative depths of abstraction and discharge structures in the headpond and tailpond can have profound impacts on water temperature and water quality, where they differ between the headpond and tailpond. However, there may be practical engineering reasons why this is unavoidable.	Ness. Montane climate similar to Loch Ness. Outlet modelled within epilimnion, which is similar to the Proposed Development.

3.4 Potential Water Quality and Biological Impacts

3.4.1 The operation of PSH projects may have adverse impacts on water quality, biological processes and aquatic habitats. Effects linked to potential changes in seasonal stratification are complex and interrelated as shown in **Figure 5 Flowchart of different effects PSH can have on the aquatic environment (Simmons et al., 2023)** as summarised by Simmons et al. 2023[69]. The impacts outlined in red are considered by this review as these are associated with changes in stratification. There are also other impacts and impact mechanisms that are considered that are not captured by **Figure 5 Flowchart of different effects PSH can have on the aquatic environment (Simmons et al., 2023)**.

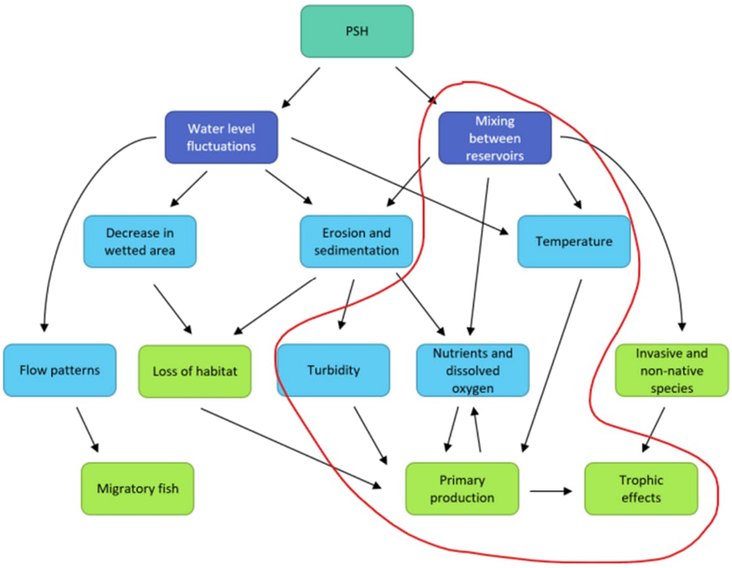

Figure 5 Flowchart of different effects PSH can have on the aquatic environment (Simmons et al., 2023)

Phytoplankton and Zooplankton

3.4.2 Tippett (1978)[47] found that the productivity of phytoplankton reduced around the vicinity of the Cruachan Hydro Scheme power station outfall. It is not clear what the causal mechanisms were for these effects, but the regular passing of water between the headpond and Loch Awe via turbines and screens and the increased mixing in the vicinity of the tailpond inlet / outlet may contribute to it. It is possible that similar changes to phytoplankton may occur in the vicinity of the Lower Control Works for the Proposed Development during operation. A reduction in algal abundance may reduce the risk of algal blooms occurring if it dampens productivity, although as discussed in the following section, the conditions for algal blooms are complex and there are many other variables to consider. The impact would also likely be localised and would not affect productivity elsewhere in the loch.

3.4.3 It is believed that the operation of PSH schemes may enhance mixing of the receiving water body. As discussed in Gray et al. (2020)[70], the depth of the mixed layer is fundamental for phytoplankton growth because it affects the availability of light and nutrients and thus their vertical distribution and the rate of sinking losses (Diehl, 2002[71]; Ptacnik, Diehl & Berger, 2003[72]; Huisman et al., 2004[73]). Deeper mixed layers can create a lower light environment, reduce sinking losses and increase nutrient availability. Shallow mixed layers may have increased light availability and sinking losses but reduce nutrient availability (Diehl et al. 2002[73]; Huisman, van Oostveen & Weissing, 1999[74]). As different species of phytoplankton have different affinities for light and levels of motility,

[69] Simmons, O.M., Foldvik, A., Sundt-Hansen, L. and Aronsen, T., 2023. A review of the environmental impacts of proposed pumped storage hydropower projects in Loch Ness: implications for migrating Atlantic salmon.
[70] Gray, E., Mackay, E.B., Elliott, J.A., Folkard, A.M. and Jones, I.D., 2020. Wide-spread inconsistency in estimation of lake mixed depth impacts interpretation of limnological processes. Water Research, 168, p.115136.
[71] Diehl, S., Berger, S., Ptacnik, R. and Wild, A., 2002. Phytoplankton, light, and nutrients in a gradient of mixing depths: field experiments. Ecology, 83(2), pp.399-411.
[72] Ptacnik, R., Diehl, S. and Berger, S., 2003. Performance of sinking and nonsinking phytoplankton taxa in a gradient of mixing depths. Limnology and Oceanography, 48(5), pp.1903-1912.
[73] Huisman, J., Sharples, J., Stroom, J.M., Visser, P.M., Kardinaal, W.E.A., Verspagen, J.M. and Sommeijer, B., 2004. Changes in turbulent mixing shift competition for light between phytoplankton species. Ecology, 85(11), pp.2960-2970.
[74] Huisman, J.E.F., van Oostveen, P. and Weissing, F.J., 1999. Critical depth and critical turbulence: two different mechanisms for the development of phytoplankton blooms. Limnology and Oceanography, 44(7), pp.1781-1787.

changes in the mixed depth can result in large shifts in taxonomic composition (Huisman et al., 2004[75]; Lehman, Mugidde, & Lehman, 1998[76]). Generally, sinking phytoplankton (e.g. diatoms and chlorophytes that are adapted to low light conditions) tend to dominate in deeper layers, whereas buoyant or motile phytoplankton (buoyant cyanobacteria and flagellates) are more abundant in shallow mixed layers (Jäger, Diehl & Schmidt, 2008[77]; Ptacnik, Diehl & Berger, 2003[78]; Visser et al., 1996[79]; Reynolds et al., 1983[80]).

3.4.4 A depressed thermocline will result in deeper circulation in the epilimnion, and this can convey phytoplankton away from the surface and potentially beyond the euphotic zone where photosynthesis is not possible. In the case of Loch Ness, the depth of the mixed layer is reported to be at least c. 30 m deep in the summer, and this is likely to already inhibit the growth of phytoplankton.

3.4.5 Changes in water column structure, and in particular a deepening of the thermocline, could also result in impacts on aquatic organisms that have adapted to take advantage of the depth of the thermocline. For example, if a deeper mixed upper layer has a greater impact on zooplankton grazers than phytoplankton, the absence of the same level of predation may lead to an early winter bloom. If the deeper upper water mixing is maintained by the continued operation of a PSH, the predator-prey imbalance may be sustained and this could result in the perpetuation of the bloom in the spring (Behrenfield and Boss, 2014[81]).

3.4.6 If the operation of a PSH scheme resulted in warming the tailpond it could encourage phytoplankton growth as it influences the rate of photosynthesis. Different species will respond to warming at different rates (Reynolds, 2006[82]), and cyanobacteria may have a competitive advantage (Gray et al., 2020[83]; Carey et al., 2012[84]; Paerl and Paul, 2012[85]; Paerl & Huisman, 2009[86]). Phenological changes resulting from changes to the timing or duration of stratification may also affect the abundance of certain phytoplankton types, also potentially leading to more frequent cyanobacteria blooms. However, any increases in turbidity may reduce light availability, which would inhibit phytoplankton growth, although this is not expected for the Proposed Development. Overall, shifts in phytoplankton community composition and abundance can have consequences for higher trophic levels and water quality (Huisman et al., 2018[87]; Winder and Sommer, 2012[88]). Changes in nutrients and growth rates are covered in more detail in the following section.

3.4.7 Overall, phytoplankton are most likely to be directly impacted by changes in stratification and water chemistry, and as they essential for supporting higher trophic levels and algal blooms, a phytoplankton focused approach has been used to try and explain the complex changes that may occur as a result of a change to seasonal stratification and these are presented in Error! Reference source not found.. These changes may have positive or negative effects on water quality, biological processes, and the composition and / or abundance of aquatic organisms.

[75] Huisman, J., Sharples, J., Stroom, J.M., Visser, P.M., Kardinaal, W.E.A., Verspagen, J.M. and Sommeijer, B., 2004. Changes in turbulent mixing shift competition for light between phytoplankton species. Ecology, 85(11), pp.2960-2970.
[76] Lehman, J.T., Mugidde, R. and Lehman, D.A., 1998. Lake Victoria plankton ecology: Mixing depth and climate-driven control of lake condition. Environmental change and response in East African Lakes, pp.99-116.
[77] Jäger, C.G., Diehl, S. and Schmidt, G.M., 2008. Influence of water-column depth and mixing on phytoplankton biomass, community composition, and nutrients. Limnology and oceanography, 53(6), pp.2361-2373.
[78] Ptacnik, R., Diehl, S. and Berger, S., 2003. Performance of sinking and nonsinking phytoplankton taxa in a gradient of mixing depths. Limnology and Oceanography, 48(5), pp.1903-1912.
[79] Visser, P., Ibelings, B.A.S., Van Der Veer, B., Koedood, J.A.N. and Mur, R., 1996. Artificial mixing prevents nuisance blooms of the cyanobacterium Microcystis in Lake Nieuwe Meer, the Netherlands. Freshwater Biology, 36(2), pp.435-450.
[80] Reynolds, C.S., Wiseman, S.W., Godfrey, B.M. and Butterwick, C., 1983. Some effects of artificial mixing on the dynamics of phytoplankton populations in large limnetic enclosures. Journal of Plankton Research, 5(2), pp.203-234.
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[82] Reynolds, C.S., 2006. The ecology of phytoplankton. Cambridge University Press.
[83] Gray, E., Mackay, E.B., Elliott, J.A., Folkard, A.M. and Jones, I.D., 2020. Wide-spread inconsistency in estimation of lake mixed depth impacts interpretation of limnological processes. Water Research, 168, p.115136.
[84] Carey, C.C., Ibelings, B.W., Hoffmann, E.P., Hamilton, D.P. and Brookes, J.D., 2012. Eco-physiological adaptations that favour freshwater cyanobacteria in a changing climate. Water research, 46(5), pp.1394-1407.
[85] Paerl, H.W. and Paul, V.J., 2012. Climate change: links to global expansion of harmful cyanobacteria. Water research, 46(5), pp.1349-1363.
[86] Paerl, H.W. and Huisman, J., 2009. Climate change: a catalyst for global expansion of harmful cyanobacterial blooms. Environmental microbiology reports, 1(1), pp.27-37.
[87] Huisman, J., Codd, G.A., Paerl, H.W., Ibelings, B.W., Verspagen, J.M. and Visser, P.M., 2018. Cyanobacterial blooms. Nature Reviews Microbiology, 16(8), pp.471-483.
[88] Winder, M. and Sommer, U., 2012. Phytoplankton response to a changing climate. Hydrobiologia, 698, pp.5-16.

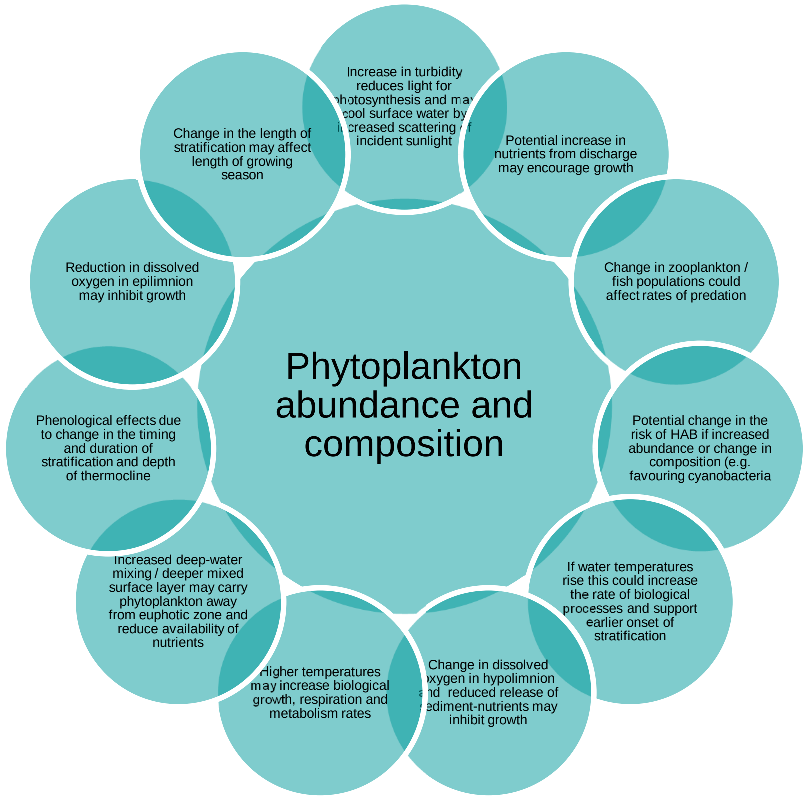

Figure 6 Potential impacts on phytoplankton from changes in stratification caused by PSH operation

Algal Blooms

3.4.8 Algal blooms are the rapid growth of algae or algae-like bacteria in a water body. In some lochs, algal blooms are a natural occurrence, particularly where there is an abundance of nutrients and periods of quiescent climatic conditions. Harmful algal blooms (HAB) occur when colonies of algae grow at a rapid rate and produce toxins or have other harmful effects on people, marine animals, terrestrial animals, birds and water quality.

3.4.9 Many HAB occur due to excessive growth of blue-green algae (i.e. cyanobacteria). However, diatoms and dinoflagellates also produce cyanotoxins/neurotoxins (Catherine et al., 2013[89]). Non-toxic algal blooms can also increase turbidity and deplete oxygen levels within a water body as they decay and sink to the bottom. In addition, as algae grow, they consume carbon dioxide and this can result in increases in water pH, which may give certain algal species a competitive advantage. This is also relevant to a range of water quality and biological processes, noting that Loch Ness has a low acid neutralising capacity due to very low alkalinity. Where the water body thermally stratifies, the decay and decomposition of algae can accelerate the depletion of dissolved oxygen in the hypolimnion and thus may exacerbate the risk of poorer water quality upon overturn. More anoxic conditions in the hypolimnion may encourage further release of sediment-derived nutrients and the potential to seed additional algal blooms following overturn. When algae bloom, they absorb significant amounts of resources reducing their availability for other organisms. They may also secrete phytotoxic and biotoxic substances that inhibit the normal growth and reproduction of other species (Zhang et al., 2024[90]). Large and dense algal blooms may also smother littoral habitats and substrates within a water body and reduce light availability for photosynthesis by blocking sunlight at the surface. It is also aesthetically unpleasant, which can be important in an area important for recreational activities and tourism.

3.4.10 The occurrence of HABs is environment-dependent, responding to nutrient accessibility, temperature and light availability in vulnerable freshwater systems, with climate change potentially encouraging more frequent events due to a combination of warmer water temperatures, more UV radiation penetrating further into the water column, plus extra nutrient loading giving certain algae a competitive advantage over other aquatic organisms (Zhang et

[89] Catherine, Q., Susanna, W., Isidora, E.S., Mark, H., Aurelie, V. and Jean-François, H., 2013. A review of current knowledge on toxic benthic freshwater cyanobacteria–ecology, toxin production and risk management. Water research, 47(15), pp.5464-5479.

[90] Zhang, P., Li, K., Liu, Q., Zou, Q., Liang, R., Qin, L. and Wang, Y., 2024. Thermal stratification characteristics and cooling water shortage threats for reservoir–green data centers under extreme climates: A case study of a large pumped storage power station reservoir. Renewable Energy, p.120697.

al., 2024[91]). HABs occur seasonally as these key environmental parameters fluctuate in freshwaters, which leads to the successive occurrence of HABs and their toxins. Cyanobacterial blooms tend to dominate in the summer, whereas diatoms and dinoflagellates are most numerous in the winter-spring period (Zhang et al., 2024[93]). Changes to water temperature (absolute increase and the duration of the growing season) during stratification and/or changes to the depth of the mixed surface layer can encourage the growth of cyanobacteria, particularly during the summer and autumn when they tend to dominate.

3.4.11 The factors controlling algal blooms are numerous and the processes complex. Gai et al. (2023)[92] used a 3D eco-hydrological model to simulate phytoplankton growth in a reservoir (Three Gorges, China) and demonstrated that vertical mixing is the main inhibitor on blooms in cold months, and horizontal advection in warmer months. Summer stratification is one of the factors influencing the growth of phytoplankton, and thus altering stratification may alter the frequency, location and/or timing of algal blooms.

3.4.12 Shorter periods of stratification or maintaining a fully mixed water column reduces the potential for poorer water quality to form in bottom waters, particularly the release of bioavailable nutrients that can encourage the growth of phytoplankton and potentially lead to algal blooms occurring under certain conditions. Preventing stratification is one method that can be applied to control algal blooms where internal recycling of nutrients is a primary factor as it reduces the release of sediment-derived nutrients under anoxic bottom water conditions and increases the mixing depth of nuisance blue-green algae, removing them from the euphotic zone to darker depths where they cannot photosynthesise (Toffolon et al. 2013)[93].

3.4.13 It is not anticipated that water in the Headpond will be significantly enriched by nutrients compared to Loch Ness, as the water in the Headpond would be abstracted from Loch Ness and the Headpond has a very small catchment. Over time, sediment may build up in the Headpond, which raises the possibility of persistent recycling of nutrients and an increasing source of excess nutrients to Loch Ness. However, sediment build up rates are expected to be low because of the character of the upland catchment and likely low primary productivity in the Headpond (as is the case in Loch Ness). Regular generation cycles will also reduce the potential for the Headpond to stratify and the risk of anoxic bottom water conditions developing that encourage the release of sediment-derived phosphorus. The build-up of sediments could be monitored and at an appropriate point in the future, excess sediment could be removed for disposal in accordance with waste legislation prevailing at the time. The risk of nutrient enrichment is greater if water in the Headpond became stagnant for an extended period of time and nutrients were allowed to build up, but this is unlikely to be the case other than planned maintenance or an emergency shut down.

3.4.14 The temperature of the discharge is also expected to be similar to the temperature of surface water in Loch Ness, perhaps slightly warmer as discussed earlier, but not significantly so. In terms of light, the operation of the Proposed Development, if anything, may slightly deepen the mixed zone in and around the intake-outlet, although as the mixed zone in Loch Ness under stratification is already quite deep this is not likely to result in material changes to the light availability for phytoplankton (i.e. deep mixing currently occurs and will likely continue to occur). Increased mixing itself may also inhibit a bloom forming by redistributing phytoplankton and carrying them deeper and away from the euphotic zone. Although it is not predicted that the operation of the Proposed Development would lead to a fundamental change to water column structure during the summer, if anything, the most likely change would be a deepening of the mixed surface zone. Should this occur it could encourage deeper mixing and potentially carry phytoplankton biomass to deeper levels where photosynthesis is reduced or not possible, although the mixed zone in Loch Ness is already very deep. If operation results in a slight delay to the onset of stratification due to enhanced mixing and the overall period of stratification is reduced, this may also reduce the time for available dissolved oxygen in the hypolimnion to be consumed and thus lower the potential for anoxic bottom waters to form and the subsequent release of sediment derived nutrients.

3.4.15 The operation of the Proposed Development is not likely to result in any significant increased risk in the potential for harmful algal blooms to occur. Loch Ness does not have a history of frequent or regular harmful algal blooms and has low productivity that is probably a result of limited light availability for most of the year, and perhaps nutrients during the summer months when there is more demand from phytoplankton. The phytoplankton population is dominated by diatoms that tend to bloom in the winter when the water column is fully mixed and when any changes in stratification are not apparent. Indeed, interruption of stratification is considered a way of

[91] Zhang, P., Li, K., Liu, Q., Zou, Q., Liang, R., Qin, L. and Wang, Y., 2024. Thermal stratification characteristics and cooling water shortage threats for reservoir–green data centers under extreme climates: A case study of a large pumped storage power station reservoir. Renewable Energy, p.120697.
[92] Gai, B., Sun, J., Lin, B., Li, Y., Mi, C. and Shatwell, T., 2023. Vertical mixing and horizontal transport unravel phytoplankton blooms in a large riverine reservoir. Journal of Hydrology, 627, p.130430.
[93] Toffolon, M., Ragazzi, M., Righetti, M., Teodoru, C.R., Tubino, M., Defrancesco, C. and Pozzi, S., 2013. Effects of artificial hypolimnetic oxygenation in a shallow lake. Part 1: Phenomenological description and management. Journal of environmental management, 114, pp.520-529.

managing the risk from harmful algal blooms, especially in smaller water bodies that can be more easily manipulated.

4 Influence of Climate Change

4.1.1 The impacts of climate change on lakes and limnological and catchment processes will be complex and varied (Battarbee, R.W., et al., 2002)[94]. However, it is important to understand how climate change may affect stratification and lake processes, and then what the implications are with the operation of the Proposed Development. The following is a review of literature concerned with these effects. It highlights how climate change may affect Loch Ness and what the implications are with the Proposed Development in operation.

4.1.2 A report on behalf of the Centre of Expertise for Waters (CREW) by May et al. (2022)[95] identified that the depth and duration of thermal stratification in Scotland's larger water bodies may be affected by increased temperatures caused by climate change, with resultant heat stress on organisms within the water body. Periods of extreme warm temperatures and the duration of these heatwaves may increase, and this can lead to low oxygen levels and result in harmful effects to aquatic life such as fish (Arvola et al., 2010)[96]. However, this is likely to be more significant in small and shallow lakes that are more vulnerable to changes.

4.1.3 Lake systems are closely coupled to the climate and thus warmer temperatures, more extreme rainfall events, and the frequency of heatwaves are predicted to impact them through increasing water temperatures, changes in water levels, increased flushing rates, and nutrient availability from the catchment. Lakes are expected to respond to these climatic factors through changes to water column structure, the duration of stratification, and the depth of the thermocline, and these changes will have implications for water quality, biological processes, and the abundance and composition of aquatic organisms (May et al., 2022[95]; Woolway et al., 2021[97]; Bayer, 2013[98]). Impacts may include:

- Higher spring temperatures may result in the earlier onset of stratification. Higher autumn temperatures may also maintain stratification, although this is less certain (Gray et al., 2020)[99].
- The prolongation of stratification will lengthen the phytoplankton growing season (Elliott, J.A., 2012)[100], increase the possibility of anoxic bottom waters forming and nutrient mineralisation and phosphorus release from lake sediments (Woolway et al., 2021)[97].
- Higher temperatures but more frequent periods of low wind speeds strengthen stratification but inhibit mixing resulting in shallower mixed surface layers. Increased air temperatures and wind speeds are thought to be the main influences on the timing of the onset and break down of stratification (Woolway et al., 2021[97]; Bayer, 2013[98]).
- Phenological changes (i.e. seasonal patterns) may change the abundance of certain phytoplankton types (Elliott, J.A., 2012)[101].
- As discussed earlier, a deeper mixed surface layer will affect the availability of light and nutrients for phytoplankton and can inhibit their growth and thus change abundance and the composition of the population.
- Water temperature directly affects phytoplankton growth as it influences the rate of photosynthesis, although different species will respond to warming at different rates (Reynolds, 2006[102]). Faster growing smaller phytoplankton species that are more efficient at nutrient uptake may benefit from

[94] Battarbee, R.W., Grytnes, J.A., Thompson, R., Appleby, P.G., Catalan, J., Korhola, A., Birks, H.J.B., Heegaard, E. and Lami, A., 2002. Comparing palaeolimnological and instrumental evidence of climate change for remote mountain lakes over the last 200 years. Journal of Paleolimnology, 28, pp.161-179.
[95] May, L., Taylor, P., Gunn, I.D., Thackeray, S.J., Carvalho, L.R., Hunter, P., Corr, M., Dobel, A.J., Grant, A., Nash, G. and Robinson, E., 2022. Assessing climate change impacts on the water quality of Scottish standing waters. Centre of Expertise for Waters (CREW).
[96] Arvola, L., George, G., Livingstone, D.M., Järvinen, M., Blenckner, T., Dokulil, M.T., Jennings, E., Aonghusa, C.N., Nõges, P., Nõges, T. and Weyhenmeyer, G.A., 2010. The impact of the changing climate on the thermal characteristics of lakes. The impact of climate change on European lakes, pp.85-101.
[97] Woolway, R.I., Sharma, S., Weyhenmeyer, G.A., Debolskiy, A., Golub, M., Mercado-Bettín, D., Perroud, M., Stepanenko, V., Tan, Z., Grant, L. and Ladwig, R., 2021. Phenological shifts in lake stratification under climate change. Nature communications, 12(1), p.2318.
[98] Bayer, T.K., 2013. Effects of climate change on two large, deep oligotrophic lakes in New Zealand (Doctoral dissertation, University of Otago).
[99] Gray, E., Mackay, E.B., Elliott, J.A., Folkard, A.M. and Jones, I.D., 2020. Wide-spread inconsistency in estimation of lake mixed depth impacts interpretation of limnological processes. Water Research, 168, p.115136.
[100] Elliott, J.A., 2012. Predicting the impact of changing nutrient load and temperature on the phytoplankton of England's largest lake, Windermere. Freshwater Biology, 57(2), pp.400-413.
[101] Elliott, J.A., 2012. Is the future blue-green? A review of the current model predictions of how climate change could affect pelagic freshwater cyanobacteria. Water research, 46(5), pp.1364-1371.
[102] Reynolds, C.S., 2006. The ecology of phytoplankton. Cambridge University Press.

warmer water temperatures (Rasconi et al., 2015[103]), as certain types of cyanobacteria that have higher optimum temperatures for growth (Carey et al., 2012[104]; Paerl and Paul, 2012[105]).

- Shifts in phytoplankton community composition and abundance can also have consequences for higher trophic levels and water quality (Huisman et al., 2018[106]; Winder and Sommer, 2012[107]).

4.1.4 Warming and shallowing of mixed surface waters may encourage phytoplankton growth but favour development of cyanobacteria (Gray et al., 2020[108]). However, where the mixed depth is already deep, material changes in phytoplankton abundance and composition are less likely (Gray et al., 2020[110]). Modelling increased flushing rates and lake water temperatures using PROTECH (Elliott, J.A., 2021[109]) on Loch Leven, Elliot and Defew (2012)[110] found that annual mean total chlorophyll-*a* did not significantly increase but that there were changes in population composition. This is likely because of limitations on growth by nutrient availability [or perhaps light in the case of Loch Ness], and since the changes resulted in some species responding positively and some negatively, but one species always benefited thus maintaining the overall biomass.

4.1.5 The reduced or ceased fertilisation of lakes in Europe has led to the restoration of oligotrophic lake bodies with low nutrients and reduced frequency of algal blooms. Yankova et al. (2017)[111] describes how climate change induced lake warming has accelerated the lowering of nutrient levels as rising air temperatures lead to stabilising of water columns and reduction in phosphorus movement. More pronounced stratification has prevented thorough mixing of the water column which has impeded the down-welling of oxygen rich surface water and the up-welling of phosphorus and nitrogen rich bottom waters that are needed to support algal spring blooms. Furthermore, the lack of overturn results in the epilimnion being depleted of phosphorus and the limitation of this nutrient is thought to have prevented spring phytoplankton blooms in Lake Zurich (Switzerland). As the operation of the PSH may encourage mixing of the surface waters it may to some extent offset any climate change driven strengthening of stratification.

4.1.6 The pattern of lake warming due to climate change is complex and varies globally (O'Reilly et al., 2015[112]), seasonally (Winslow et al., 2017[113]), with lake size (Woolway et al., 2016[114]), and vertically within lakes (Winslow et al., 2015[115]). The effect of rising water temperatures, and to a lesser extent flushing rates and potentially increased nutrient loads (although not likely given the small residual catchment for the proposed Headpond and regular abstraction from Loch Ness), may be considered proxies for possible effects of the operation of a PSH scheme as there is evidence that they can lead to lake warming (Bonalumi et al., 2012[116]). However, the very large volume and high heat inertia of Loch Ness may dampen the effects in the same way it delays the onset of natural stratification. More significant warming may be required to result in a change in stratification, overcoming wind induced mixing, than would be the case in a smaller and shallower water body. As Loch Ness is highly exposed to prevailing winds with a relatively long fetch, the influence of wind is likely to be more significant which may maintain mixed depth and resist shallowing. The very low nutrient levels and rates of primary productivity in

[103] Rasconi, S., Gall, A., Winter, K. and Kainz, M.J., 2015. Increasing water temperature triggers dominance of small freshwater plankton. PloS one, 10(10), p.e0140449.
[104] Carey, C.C., Ibelings, B.W., Hoffmann, E.P., Hamilton, D.P. and Brookes, J.D., 2012. Eco-physiological adaptations that favour freshwater cyanobacteria in a changing climate. Water research, 46(5), pp.1394-1407.
[105] Paerl, H.W. and Paul, V.J., 2012. Climate change: links to global expansion of harmful cyanobacteria. Water research, 46(5), pp.1349-1363.
[106] Huisman, J., Codd, G.A., Paerl, H.W., Ibelings, B.W., Verspagen, J.M. and Visser, P.M., 2018. Cyanobacterial blooms. Nature Reviews Microbiology, 16(8), pp.471-483.
[107] Winder, M. and Sommer, U., 2012. Phytoplankton response to a changing climate. Hydrobiologia, 698, pp.5-16.
[108] Gray, E., Mackay, E.B., Elliott, J.A., Folkard, A.M. and Jones, I.D., 2020. Wide-spread inconsistency in estimation of lake mixed depth impacts interpretation of limnological processes. Water Research, 168, p.115136.
[109] Elliott, J.A., 2021. Modelling lake phytoplankton communities: recent applications of the PROTECH model. Hydrobiologia, 848(1), pp.209-217.
[110] Elliott, J.A. and Defew, L., 2012. Modelling the response of phytoplankton in a shallow lake (Loch Leven, UK) to changes in lake retention time and water temperature. Loch Leven: 40 years of scientific research: Understanding the links between pollution, climate change and ecological response, pp.105-116.
[111] Yankova, Y., Neuenschwander, S., Köster, O. and Posch, T., 2017. Abrupt stop of deep water turnover with lake warming: Drastic consequences for algal primary producers. Scientific Reports, 7(1), p.13770.
[112] O'Reilly, C.M., Sharma, S., Gray, D.K., Hampton, S.E., Read, J.S., Rowley, R.J., Schneider, P., Lenters, J.D., McIntyre, P.B., Kraemer, B.M. and Weyhenmeyer, G.A., 2015. Rapid and highly variable warming of lake surface waters around the globe. Geophysical Research Letters, 42(24), pp.10-773.
[113] Winslow, L.A., Read, J.S., Hansen, G.J., Rose, K.C. and Robertson, D.M., 2017. Seasonality of change: Summer warming rates do not fully represent effects of climate change on lake temperatures. Limnology and Oceanography, 62(5), pp.2168-2178.
[114] Woolway, R.I., Cinque, K., de Eyto, E., DeGasperi, C., Dokulil, M., Korhonen, J., Maberly, S., Marszelewski, W., May, L., Merchant, C.J. and Paterson, A., 2016. Lake surface temperature [in" State of the climate in 2015"]. Bulletin of the American Meteorological Society, 97(8), pp.S17-S18.
[115] Winslow, L.A., Read, J.S., Hansen, G.J. and Hanson, P.C., 2015. Small lakes show muted climate change signal in deepwater temperatures. Geophysical Research Letters, 42(2), pp.355-361.
[116] Bonalumi, M., Anselmetti, F.S., Wüest, A. and Schmid, M., 2012. Modeling of temperature and turbidity in a natural lake and a reservoir connected by pumped-storage operations. Water Resources Research, 48(8).

Loch Ness may also mean there is greater resistance to increased growth of phytoplankton from warming, either due to climate change or the operation of PSH project.

5 Other PSH Schemes

5.1.1 A review of Environmental Impact Assessments and related published information for other existing and proposed PSH schemes in Scotland, the UK and internationally, has been undertaken. Analysis of the results of this review highlights what the key issues associated with PSH schemes are, the range of environmental impact assessments that have been carried out, and any variation in detail and approach to those assessments. **Table 4 Existing and proposed PSH schemes in Scotland and the wider UK** summarises known existing and proposed pumped storage hydro schemes in Scotland (shown on **Figure 7 Locations of existing and proposed PSH schemes in Scotland**) and the wider UK.

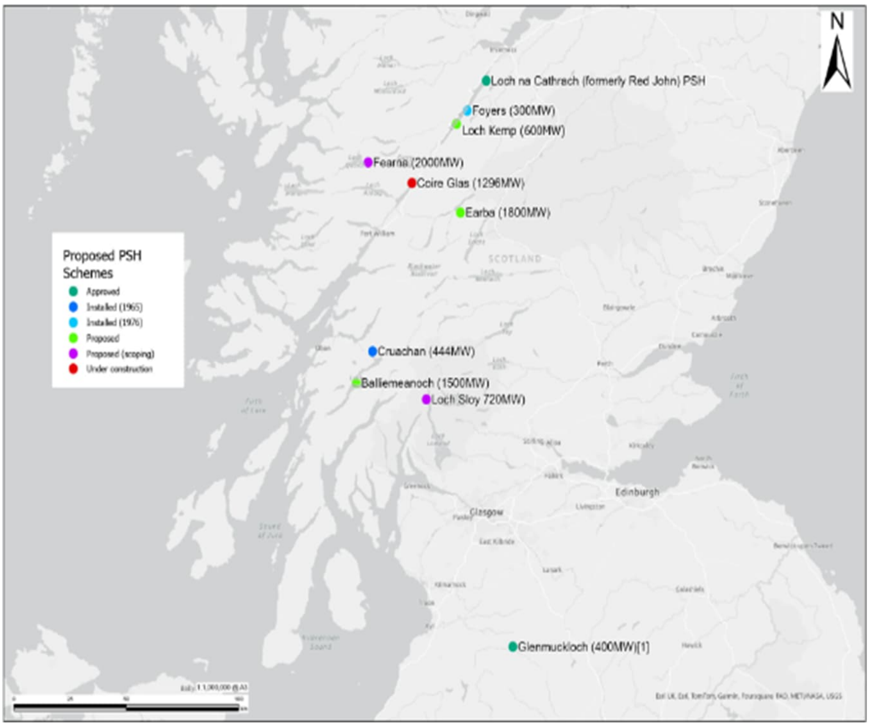

Figure 7 Locations of existing and proposed PSH schemes in Scotland

Table 4 Existing and proposed PSH schemes in Scotland and the wider UK

PSH Scheme (incl. MW)	Status	Source	Location (incl. approx. NGR)	Open or closed system (incl. tail pond)	Impact assessment summary
Cruachan (444 MW)	Installed (1965)	Tippett (1978)	Loch Awe, Argyll and Bute, Western Scotland (NN 08170 28610)	Open (Loch Awe)	Post operation assessment of impact on thermocline changes and plankton impacts.
Cruachan 2 (+600 MW)	Approved	EIAR (Drax, 2022)[117]	Loch Awe, Argyll and Bute, Western Scotland (NN 08170 28610)	Open (Loch Awe)	No assessment of potential changes to thermal stratification, warm water discharges (mixed conditions) or other associated ecological effects.
Loch Kemp (600 MW)	Proposed	EIAR (Ash, 2023)	Northeast Loch Ness, Highlands, Scotland (NH 45480 16640)	Open (Loch Ness)	Qualitative assessment of potential changes to thermal stratification and risk of encouraging algal blooms, plus TUFLOW modelling of warm water discharges (mixed conditions)

[117] https://www.cruachanexpansion.com/wp-content/uploads/2022/05/Cruachan-Expansion-Project-Volume-1-EIA-Report.pdf).

PSH Scheme (incl. MW)	Status	Source	Location (incl. approx. NGR)	Open or closed system (incl. tail pond)	Impact assessment summary
Balliemeanoch (1500 MW)	Proposed	EIAR (AECOM, 2023)	Loch Awe, Argyll and Bute, Scotland (NN 00920 16190)	Open (Loch Awe)	Qualitative assessment of potential changes to thermal stratification, warm water discharges (mixed conditions) and risk of encouraging algal blooms.
Loch na Cathrach (formerly Red John) PSH (450 MW)	Approved	EIAR (AECOM, 2018)	Northeast Loch Ness, Highlands, Scotland (NH 58790 33350)	Open (Loch Ness)	Qualitative assessment of potential changes to thermal stratification, warm water discharges (mixed conditions) and risk of encouraging algal blooms.
Foyers (300 MW)	Installed (1976)	SSE Renewables (2024)118119	Central Loch Ness, Highlands, Scotland (NH 50310 21780)	Open (Loch Ness	No assessment of potential changes to thermal stratification, warm water discharges (mixed conditions) or other associated ecological effects.
Glenmuckloch (400 MW)120	Approved	EIAR (Arup, 2021)	Near Kirkconnel, Dumfries and Galloway, Scotland (NS 70600 14240)	Closed	As a closed system between two purpose-built reservoirs there was no requirement to consider assessment of impacts on thermal stratification in natural water body.
Coire Glas (1296 MW)	Under construction	Revised EIAR (SSE Renewables 2018)[121]	Loch Lochy, Highlands, Scotland (NN 25700 93760)	Open (Loch Lochy)	No assessment of potential changes to thermal stratification, warm water discharges (mixed conditions) or other associated ecological effects.
Loch Sloy (720 MW)	Proposed (scoping)	Sloy Pumped Storage Scheme Scoping Report (SSE Renewables, 2023)[122]	Northern basin Loch Lomond, Argyll and Bute, Scotland (NN 32100 09840)	Open (Loch Lomond)	No assessment of potential changes to thermal stratification or warm water discharges (mixed conditions) proposed. The 2009 assessment for the consented scheme but not built concluded that there would be no significant effects from the mixing of waters from the two lochs in Loch Sloy on aquatic ecology, so no assessment was undertaken.
Earba (1800 MW)	Proposed	Gilkes Energy EIAR (2024, 2023)[123124]	Lochan na Earba (near Dalwhinnie), Highlands, Scotland (NN 47310 82320)	Open (Lochan na Earba)	Cursory and qualitative assessment of potential impacts on thermal stratification and algal blooms but no baseline information.
Fearna (1800 MW)	Proposed (scoping)	Gilkes Energy Scoping Report (2024)[125]	Loch Quoich, Highlands, Scotland (NH 06200 01730)	Open (Loch Quoich)	No assessment of potential changes to thermal stratification, warm water discharges (mixed conditions) or other associated ecological effects.
Dinorwig (1728MW)	Installed (1984)	Engie (2024) NS Energy (2020)	North Wales (SH 59320 59990)	Open (Llyn Peris	Due to the age of this existing development no information can be found on any environmental assessments that were carried out.

[118] https://www.sserenewables.com/hydro/foyers/
[119] https://www.sse.com/media/aybjsta2/in110_foyers_open_day_v3.pdf
[120] https://www.energyconsents.scot/ApplicationDetails.aspx?cr=ECU00003259&T=5
[121] https://www.coireglas.com/planning-documents
[122] https://www.sserenewables.com/media/4qkj4hpo/volume-4-appendix-6-1-scoping-report.pdf
[123] https://her.highland.gov.uk/api/LibraryLink5WebServiceProxy/FetchResourceFromStub/1-3-1-3-2-5_666669814d430a2-131325_3841752c36a307f.pdf
[124] https://www.energyconsents.scot/ApplicationDetails.aspx?cr=ECU00005062
[125] https://www.energyconsents.scot/ApplicationDetails.aspx?cr=ECU00005061

PSH Scheme (incl. MW)	Status	Source	Location (incl. approx. NGR)	Open or closed system (incl. tail pond)	Impact assessment summary
Ffestiniog (300 MW)	Installed (1963)	Engie (2024) Power Technology (2024)	North Wales (SH 67920 44400)	Open (Tan-y-Grisiau Reservoir)	Due to the age of this existing development no information can be found on any environmental assessments that were carried out.

5.1.2 Of the PSH schemes that have been subject to recent environmental assessment, **Table 5 Summary of environment assessment for existing and proposed PSH schemes in Scotland and the wider UK** provides a summary of the outcome. In the UK context, detailed assessment of potential impacts on seasonal thermal stratification of relevant water bodies is not routinely identified by regulators as a key issue and in the majority of cases the potential impacts of proposed PSH schemes on thermal stratification have not been assessed at all. Where assessments have been undertaken, they have been predominantly qualitative and precautionary. Where predicted effects are uncertain the need for further monitoring and potentially assessment or operational controls remains a possibility.

Table 5 Summary of environmental assessment for existing and proposed PSH schemes in Scotland and the wider UK

PSH Scheme	Scheme Summary	Potential impacts assessed, scope of assessment and outcome
Cruachan	Existing PSH scheme with flow from Cruachan Reservoir into Loch Awe. 444MW. The headpond, Cruachan Reservoir, is located at NGR NN 08170 28610. It has a surface area of approx. 48 ha and a volume of c. 3,050,517 m^3.[126] Inlet / outlet located at approximately NGR NN 07866 26795. The dimensions of the existing Cruachan 1 outlet structure are not known, although for the recently consented Cruachan Expansion, the outlet is estimated to be around 18 m wide and 5 m high and discharges into the northern basin of Loch Awe where maximum water depths are up to around 74 m deep.	Loch Awe is monomictic with summer stratification in water depths greater than 25 m deep. The depth of the upper limit of thermocline is around 10-11 m early in the summer but may deepen to around 20 m depth at the solar radiation maximum. Increased mixing of the upper water column resulting in delaying the onset of stratification, sharpening and deepening the thermocline, at least during the early part of the summer before more intense solar radiation compensated for the impact. A decrease in phytoplankton populations was also observed in the vicinity of the water outflow, possibly due to increased water movement or that the organisms avoid or are killed by the turbines.
Cruachan 2	Up to an additional 600 MW on Cruachan 1 (Barry, C. & Limbrick, K., 2022). No change to the existing Cruachan Reservoir headpond. Additional new inlet / outlet located adjacent to the existing Cruachan 1 structures to the east. Maximum velocities through smolt screens will not exceed 0.3 m/s. Depth of outlet screens not known but may be c. 10-12 m.	Thermal stratification impacts not assessed in the Cruachan Expansion Project – EIA Report, Volume 1 – Main Report (Drax, May 2022).
Loch Kemp	600 MW scheme where headpond would be constructed by expanding and deepening Loch Kemp. Headpond will have a surface area of c.130 ha (maximum depth of 43 m) and a maximum storage volume of 21 Mm^3. The inlet / outlet structure would be located at NGR NH 45480 16640. The lower control works would be below the Loch Ness minimum water level (15.3 m AOD) and mostly underwater apart from approx. 1.5 m extending above the existing maximum Loch Ness surface level (17.5 m AOD). Thus, the sub-surface screen area is c. 11 m high with a diameter of 20 m. Screens with a clear opening of 12.5 mm and a maximum approach velocity limit of 0.3 m/sec will be provided.	EIAR Chapter 14 includes a qualitative assessment of potential impacts on thermal stratification but is solely qualitative and does not refer to any other specific modelling other than alluding to the fish impact study noted above. It is concluded that there would be a negligible effect on surface water [receptors] during operation, although effect scores are not itemised by impact types. No further or additional mitigation is proposed. With reference to changes to thermal stratification, the duration of the risk being limited to the warmer months of the year, the relative size of Loch Ness and the expected depth of the thermocline, and the assumption that water in the Loch Kemp headpond will not be significantly warmer are cited as reasons for this conclusion. This, plus the assumption the headpond will not contain high levels of nutrients, the low nutrient status and dilution within Loch Ness, were reasons for the risk of encouraging algal blooms being low.

[126] CEH Lakes Portal https://eip.ceh.ac.uk/apps/lakes/detail.html?wbid=23984 [accessed December 2024]

PSH Scheme	Scheme Summary	Potential impacts assessed, scope of assessment and outcome
		EIAR Chapter 13 considers potential impacts on fish including reference to thermal modelling using TUFLOW, which adopted very precautionary parameters to test a worst-case scenario.
Balliemeanoch	Proposed 1500 MW PSH with the headpond located on the site of the current Lochan Airigh (proposed volume c. 53 M m3) with Loch Awe as the tailpond (c. NGR NN 00920 16190). Maximum discharge rate of 494 cubic m3/s with velocity no greater than 0.3 m/s meaning the screens will be 148 m wide and 19 m high. The loch bed will be reprofiled and dredged to depth of c. 18.2 m AOD. Water depths of around 40 m deep lie offshore from the inlet / outlet.	The potential impact on thermal stratification on Loch Ness was not raised by statutory and non-statutory consultees. Regardless, the water environment impact assessment included a qualitative assessment of the water quality changes from changes in seasonal stratification, as well as assessment of thermal discharges during fully mixed conditions, and the potential to encourage harmful algal blooms, all based on available data. It is noted that Tippett (1978) investigated Cruachan 1, also on Loch Awe, and observed changes in the thermocline and plankton communities in the vicinity of the outfall for that PSH scheme. Loch Awe also has a higher nutrient status than Loch Ness and a history of algal blooms. Overall, a moderate adverse effect on water quality due to changes in thermal stratification was predicted on a precautionary basis and the expectation that the impact would be local to the outfall. Water quality and biological monitoring in Loch Awe was proposed as additional mitigation so that any future changes can be tracked and operation of the future PSH scheme optimised to minimise any adverse effects. Effects from thermal discharges under mixed water column conditions and encouraging algal blooms were both predicted to be minor adverse and not significant.
Loch na Cathrach (formerly Red John) PSH	Inlet / outlet located southwest of Dores approx. NGR NH 58790 33350. Headpond will hold maximum c. 4.9 Mm^3. During generation 250 m3/s will be discharged with a maximum velocity of approx. 0.15 m/s.	The potential impact on thermal stratification on Loch Ness was not raised by statutory and non-statutory consultees. Regardless, the water environment impact assessment included a qualitative assessment of the water quality changes from changes in seasonal stratification, as well as assessment of thermal discharges during fully mixed conditions, and the potential to encourage harmful algal blooms, all based on available data. However, available data was sparse. Overall, minor adverse impacts were predicted by virtue of the size of Loch Ness, assumed depth of the thermocline, low nutrient status and lack of history of algal bloom occurrence. However, recognising the uncertainty in this assessment, future water quality monitoring within the headpond was proposed to build up an understanding of how water quality may change whilst stored in comparison to background water quality in Loch Ness. This preventative measure will support decisions about operation to ensure that unforeseen water quality impacts on Loch Ness are avoided.
Foyers	Existing 300 MW combined conventional hydro and pumped storage plant located on the south side of Loch Ness (tailpond) adjacent to the mouth of the River Foyers 300 MW (NGR NH 50310 21780). The headpond is Loch Mhor (volume 31.2 Mm^3). The maximum discharge is c. 200 m^3/s.	Due to the age of this existing development no information can be found on any environmental assessments that were carried out.
Glenmuckloch [127]	This is a closed system including the construction of a new headpond (storage 3.3 Mm^3) and the repurposing of a former open cast mine as the tailpond (approx. NS 70600 14240). Proposed 400 MW scheme scheduled for opening in 2027.	As a closed system between two purpose-built reservoirs there was no requirement to consider assessment of impacts on thermal stratification in the natural water body.
Coire Glas	Proposed 1296MW PSH involving the impoundment of Coire Glas (headpond) and Loch Lochy as the tailpond. The inlet / outlet structure located at approximately NGR NN 25700 93760. Inlet / outlet screens will be approx. 200 m long and 17 m in height (mostly underwater - 1.5 m of the total height would extend above the existing maximum Loch Lochy surface level). Smolt	The EIAR does not include any assessment of potential impacts on thermal stratification or warm discharges into an isothermal loch water body. Loch Lochy has a mean depth of c. 70 m and a maximum depth of c. 160 m, and thus it would be expected to thermally stratify during the warmer months of the year. This is likely to be similar to the monomictic stratification that occurs in the relatively nearby Loch Ness. Chapter 13 'Fish' of the EIAR does consider mixing of headpond and tailpond water, but this focuses on

[127] https://www.energyconsents.scot/ApplicationDetails.aspx?cr=ECU00003259&T=5

PSH Scheme	Scheme Summary	Potential impacts assessed, scope of assessment and outcome
	screens (12 mm spacing) and a maximum approach velocity limit of 0.3 m/s.	nutrient enrichment of the headpond rather than impacts on Loch Lochy.
Loch Sloy	Existing conventional hydro power plant abstracting water from Loch Sloy and discharging to Loch Lomond (approx. NN 32103 09840) but without pumped capacity. In 2009 a project to convert to a PSH scheme was approved but the scheme was never implemented. SSE now wish to resurrect this proposal to convert the existing plant to a 720 MW PSH scheme. Currently, only the Environmental Scoping Report is publicly available.	According to the 2023 Scoping Report "*The 2009 assessment for the consented scheme concluded that there would be no significant effects from the mixing of waters from the two lochs in Loch Sloy. It noted that the increased algal concentration in the mixed water in Loch Sloy may result in increased zooplankton populations, which feed on these algae and will have a positive effect on powan from an increased food supply. It is proposed to scope out further assessment in the EIA*." The water environmental impact assessment also appears to focus on water management. No detailed assessment of potential impacts on thermal stratification is currently proposed. This is despite Loch Lomond being a monomictic lake by virtue of its temperate climate and having a mean depth of c. 37 m and a maximum depth of c. 170 m.
Earba	Proposed 1800 MW PSH scheme by raising the water level in Loch Leamhain (headpond) and Lochan na Earba (approx. NN 47310 82320). Lochan na Earba consists of two separate basins and is already modified by existing dams and a 1MW conventional hydro-electric scheme. Maximum storage would be 62 Mm^3. Three sets of twin screens are proposed with each pair c. 60 m wide and c. 18 m deep (from just above minimum water level), requiring excavation of the loch bed that would be deepened on approach. Bar screens proposed (10 mm) and the maximum intake velocity would be 0.3m/s.	EIAR Chapter 12 includes a cursory and qualitative assessment of potential impacts on thermal stratification and algal blooms, although there is no baseline information on these matters, and it is actually thermal discharges rather than impacts on any existing stratification that is assessed. This concludes that there would be no significant impact. There is also reference to future post-construction water quality monitoring, although the purpose of this is not defined. The larger of the two Lochan na Earba basins has a mean depth of c. 11 m and a maximum depth of c. 25 m[128]. Although thermal stratification might occur under certain conditions, the basin is likely to be relatively well mixed for most of the time. We note that by deepening the two lochs the potential for thermal stratification may increase, but this is not the baseline and therefore does not require consideration. Overall, the scale of the proposed development to the size of the headpond and tailpond (i.e. maximum drawdown of approx. 22 m and 70 m, respectively) means that there is likely to be significant mixing of the water column during pumping or generation.
Fearna	Proposed 1800 MW PSH scheme. Loch Quoich, which is currently used as a reservoir for conventional hydro generation and is the largest storage reservoir in the UK (dammed in the late 1950s), would be the tailpond (c. NH 06200 01730). No modifications to the existing dams or operational level range are proposed in Loch Quoich. The upper reservoir would be created by raising the level of Loch Fearna from its current level of 538m AOD to a maximum of 600m AOD to hold up to 40 Mm^3.	No assessment of potential impacts on existing thermal stratification in Loch Quoich, warm discharges under mixed conditions, or associated impacts such as risk of encouraging more frequent algal blooms is discussed in the Scoping Report (Gilkes Energy, 2024). Loch Quoich has a mean depth of c. 32 m and a maximum depth of c. 86 m, and thus thermal stratification in the warmer months of the year are possible[129]. Loch Ferna has a mean depth of 6.6 m and this is likely to be well mixed most of the time.[130]
Dinorwig	Existing PSH, water flows from manmade cavern in Elidir Fawr mountain into Llyn Peris. 1728MW. Underground headpond is 1 million m^3. Flow rate 1-8m^3 per second (normal), 60m^3 per second (maximum).	Due to the age of this existing development no information can be found on any environmental assessments that were carried out. Llyn Peris was used as the tailpond and has been substantially modified and adversely impacted by the operation of the PSH scheme, when compared to the adjacent, albeit much larger Llyn Padarn.
Ffestiniog	Existing PSH commissioned in 1963. Water flows from Llyn Stwlan into Tan-y-Grisiau. 300 MW PSH scheme with a headpond holding up to 2 million m^3. Pipelines 195 m deep, 213 m long, and flow rate 27m^3 per second.	Due to the age of this existing development no information can be found on any environmental assessments that were carried out.

5.1.3 International examples of recent PSH schemes have also been identified and these are listed in **Table 6 International existing and proposed PSH**. These references have generally been identified through other studies and thus further details on potential impacts have already been discussed in **Section 3 Potential Impacts**.

[128] https://eip.ceh.ac.uk/apps/lakes/detail.html?wbid=21823)
[129] https://eip.ceh.ac.uk/apps/lakes/detail.html?wbid=20828
[130] https://eip.ceh.ac.uk/apps/lakes/detail.html?wbid=20976

Table 6 International existing and proposed PSH

PSH Scheme (incl. MW)	Status	Source	Location (incl. approx. latitude / longitude)	Open or closed system (incl. tail pond)	Impact assessment summary
As Conchas (375 MW)	Installed	Bermudez et al (2018)[131]	Encoro das Conchas, Galicia, Spain (41.944330, 8.0347717)	Open (Encoro das Conchas)	Significant impact close to outlet, but minimal effects beyond due to size and shape of waterbody.
Lake Elsinore) (500 MW)	Proposed	Anderson (2010) [132]	Lake Elsinore, California, USA (33.660496, 117.35059)	Closed (Lake Elsinore)	Impacts minimised by design and outlet location; smaller scale of tailpond would otherwise lead to greater effects.
Grimsel II (392 MW)	Installed (1973)	Bonalumi et al (2011) [133]	Grimselsee, Switzerland (46.571961, 8.3293426)	Closed (Grimselsee)	Increased temperatures noted altering temperature gradient in water bodies modelled.
Lago Bianco (1050 MW)	Proposed	Bonalumi et al (2012) [134]	Lago Bianco, Switzerland (46.406735, 10.019596)	Open (Lago di Poschiavo)	Earlier and longer stratification period when PSH applied to model.
Kruonis (900 MW)	Installed (1992)	Gailiusis et al (2002) [135]	Kaunas Reservoir, Lithuania (54.800388, 24.244380)	Open (Kaunas Reservoir)	Altered hydrophysical regime – water levels and flow velocities. Does not discuss stratification.
Etzelwerk Altendorf (135 MW increasing to 525 MW)	Installed (1937)	Kobler et al (2018) [136]	Zürichsee, Switzerland (47.214088, 8.7649441)	Open (Zürichsee)	Increased temperatures through water column observed when PSH models ran; impacts of PSH considered small, however. Deep water withdrawal reduces impact further.

[131] https://link.springer.com/article/10.1007/s10666-017-9557-3
[132] https://www.tandfonline.com/doi/full/10.1080/10402380903479102
[133] https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2010WR010262
[134] https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2012WR011844
[135] https://iwaponline.com/hr/article/34/5/507/931/Modelling-the-Effect-of-the-Hydroelectric-Pumped
[136] https://www.mdpi.com/2071-1050/10/6/1968

6 Summary and Conclusions

6.1.1 This literature review provides background information on how PSH projects may influence stratification in deep water bodies. It does not assess the impact of the Proposed Development on stratification in Loch Ness. This assessment can be found in EIAR **Chapter 10 Water Environment (Volume 2: Main Report)**.

6.1.2 Overall, the potential impacts of the operation of PSH projects on lake stratification may include:

- Delaying, weakening or even eliminating (in shallow water bodies) stratification due to enhanced hydrodynamic mixing.
- Changes in water temperature where the discharge temperature is warmer than ambient temperatures in the tailpond. This may be from energy losses from turbines, operation of a cooling system, friction, conveyance through underground tunnels, and heating in the headpond such as from stringer lake-atmosphere coupling[137].
- Alterations to the heat exchange at the lake surface-air interface that may affect stratification, depending on the temperature of the discharge and ambient conditions in the tailpond.
- An increase in turbidity either from the quality of the discharge water or by disturbing bed sediment on release, which can potentially encourage water cooling by scattering more sunlight (and therefore influence stratification processes), although this is not considered likely for the circumstances of the Proposed Development.

6.1.3 Based on this review, there are indications that the operation of PSH projects have the potential to alter stratification in water bodies, particularly in close vicinity to the outlet/inlet, and there are examples of changes occurring. However, there are a large number of variables and a lack of detailed contemporaneous studies of PSH in Scotland. Cumulative effects and climate change are also considerations.

6.1.4 The design and depth of the outlet structure, the rate and volume of the discharge (and perhaps to a lesser extent, abstraction), the frequency and duration of operation (mainly generation but also pumping), all affect how water enters the tailpond and the energy it carries that may generate mixing. The temperature and quality of the discharge is also an important factor determining how the discharge behaves upon release and the changes to the water column characteristics that occur as a result. The relative depths, volumes, altitudes, morphology and water quality (including temperature) of the headpond and tailpond influence the characteristics of the discharge, so understanding how these may differ is potentially important. It is for these reasons that inferences from published papers and case studies need to be interpreted with care, as no two are the same. Furthermore, Loch Ness exhibits some fairly unique physical attributes that mean proxy studies may not be directly applicable. Hydrodynamic modelling of the Proposed Development will be useful to investigate the risks and optimise operation to minimise impacts and thus should form part of a suite of mitigation.

6.1.5 The potential implications of changes in stratification on water quality, biological processes and the behaviour of aquatic organisms are numerous, highly complex and inter-related. This review has highlighted how the aquatic ecosystem might adapt to changes in seasonal stratification, although the research is more limited in this area and further studies are required to improve the understanding of these possible changes. Phytoplankton are most likely to be directly impacted by changes in stratification and water chemistry, and as they essential for supporting higher trophic levels and algal blooms, a phytoplankton focused approach has been used to try and explain the complex changes that may occur as a result of a change to seasonal stratification (see Error! Reference source not found.). These changes may have positive or negative effects on water quality, biological processes, and the composition and / or abundance of aquatic organisms.

6.1.6 Notwithstanding the above, Loch Ness is a substantial water body and has a very large volume, strong internal seiche, and high heat inertia, all of which may help it to resist changes from enhanced mixing as a consequence of the operation of PSH projects. This is illustrated by the fact that the onset and break-down of natural stratification is delayed compared to other lochs. The thermocline is also already very deep at c. 30 m or maybe deeper and thus may be less likely to be influenced by discharges from PSH projects, which tend to deepen the surface mixed layer. Low nutrient concentrations and low primary productivity as a result of poor light availability also mean that phytoplankton populations may be less sensitive to changes that might otherwise encourage their growth. Phytoplankton communities in Loch Ness are also dominated by diatoms, and although they can bloom and sometimes be considered harmful, the loch does not appear to be ‘primed’ with cyanobacteria that is most

[137] However, this was reported in a single reference.

commonly associated with HAB events. Other studies assessing climate change also suggest that although composition may change, total biomass may not.

6.1.7 Controlling the energy of any discharge through outlet design and rates of discharge may reduce and minimise the potential impact on stratification. The duration, frequency and timing of operation may also reduce effects despite not being specifically assessed by published sources that have been reviewed. However, this needs to be balanced with practical and commercial considerations for operation of the Proposed Development.

6.1.8 The pattern of lake warming due to climate change is complex and varies globally, seasonally, with lake size and vertically within lakes. The effect of rising water temperatures, and to a lesser extent flushing rates and increased nutrient loads, may be considered proxies for possible effects of the operation of a PSH scheme as there is evidence that they can lead to lake warming. However, the very large volume and high heat inertia of Loch Ness may dampen the effects in the same way it delays the onset of natural stratification. Studies assessing the impact of climate change on lakes suggest that the duration of stratification will be longer, most likely through earlier onset, although prolongation into the later autumn may also occur. Warmer average air temperatures with longer periods of low winds are expected to strengthen stratification but cause a shallowing of the mixed surface layer. A discharge that is warmer than ambient conditions in the tailpond may compound this, but on the other hand enhanced mixing will tend to deepen the thermocline. Thus, the operation of a PSH project could offset some effects of climate change to an extent and locally around the outlet.

6.1.9 Finally, as stratification occurs only in the warmer months of the year in temperate monomictic lakes, changes to the water column structure will not occur all year around. There will be less effect during periods when Loch Ness is generally well-mixed and isothermal. Lake systems are dynamic, and stratification is also not constant ‘year on year’. Thus, it is possible that any changes as a result of the Proposed Development remain within natural ranges (which future monitoring will help define). Therefore, whether long-term changes in the onset of stratification occur are significant or not is difficult to say. It will also depend on how any changes influence the baseline aquatic ecosystem, and phenotypic plasticity may account for some of the change should it occur. It is known that Loch Ness has a large inertia due to its volume, morphology and exposure to wind induced circulation and a strong internal seiche and thus tends to stratify later but take a longer time for this to completely break down. Thus, stratification in Loch Ness may be more resistant to changes, even locally around the proposed outfall. The weaker stratification that occurs may also mean that it has less of an influence on water quality, biological processes and the behaviour of aquatic organisms.

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