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Towards environmental design in hydropower reservoirs

Developing a handbook for mitigation measures in regulated lakes

Ingeborg P. Helland, Stein I. Johnsen, Antti P. Eloranta

NTNU SINTEF NINA

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Abstract

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Due to their ability to store large amounts of water, reservoirs are the supporting beam in the Norwegian hydropower system. Norway has approximately 1200 lakes that are regulated for hydropower usage, but despite the large number, there is relatively little public awareness of environmental impacts in lakes regulated for hydropower, at least compared to the focus on regulated salmon rivers. The *Handbook for environmental design in regulated salmon rivers* was published in 2013 and has become an important tool for local and national authorities, as well as hydropower companies in Norway. The aim of this report is to investigate the feasibility of developing a handbook for environmental design related to fish in reservoirs, similar to the one for salmon rivers.

Given the large variation among Norwegian hydropower reservoirs, it is not realistic to create a first handbook for environmental design that will be useful for all reservoir types. Hence, it would be useful to narrow the scope and identify some reservoirs that are of particular interest and start with method development targeting these reservoirs. In this report, we have focused on environmental measures targeting brown trout populations, as this well-studied species is the most common in Norwegian hydropower reservoirs.

The first phase of the environmental design methodology is the diagnosis phase, which aims to identify key bottlenecks for fish populations. Based on many years of fish monitoring in Norwegian reservoirs, several ecological bottlenecks are already known. An aspect that is not included in the salmon handbook, but of high importance for a future handbook for reservoirs, is collecting information on lake productivity. Unlike the anadromous salmon, experiencing abundant food recourses in their oceanic stage, resident species are highly influenced by the food availability in the lake. Hence, when looking for bottlenecks in reservoirs, an additional population-regulating factor to habitat-related and hydrological conditions may be food limitation. We suggest that the diagnosis phase for environmental design for reservoirs should consist of two parts: one based on data on fish populations and their main prey, and the other on hydrological and habitat data. In addition, the hydropower system must be described to understand potential environmental impacts.

In contrast to data on fish populations and their main prey, habitat mapping and hydrological analyses have been lacking in most reservoir surveys. In many cases, appropriate habitat mapping is done in the adjacent spawning streams, but habitat mapping is rarely done within lakes. We believe it is realistic to identify bottlenecks and undertake a full diagnosis phase of environmental design based on today's knowledge. However, there is a need to implement standardized surveys to ensure that sufficient data is collected in all reservoir monitoring. In this report, we have suggested available sampling methodology that we believe should be part of such standardized surveys.

The second phase of environmental design is to identify design solutions. To our knowledge, no one has so far performed a full environmental design project in a reservoir. However, there are a number of different mitigation measures that have been used in Norwegian reservoirs and could be further developed for a future handbook. To obtain information about the type of already tested measures, we performed a survey among all County Governors in Norway. The results show that there is limited experience with mitigation measures in reservoirs. Of > 1200 Norwegian reservoirs, only 37 were reported to have known mitigation measures targeting brown trout, and a few targeting other species. Further, almost all measures targeting reservoir fishes have been implemented in the surrounding streams and rivers. These measures are more similar to the environmental design already developed for salmon rivers. For development of a handbook for reservoirs, it is important to develop environmental design methodology within the reservoir itself, i.e. in the lake habitats. The County Governors reported 14 cases of measures targeting trout within a reservoir, covering habitat-related measures, altered pattern of water level fluctuations and creation of "lake in reservoir". We find these examples particularly interesting and relevant for a future handbook for environmental design in reservoirs. Although we have some examples of existing mitigation measures to learn from, it is important to identify optimal ways to balance the need of the fish populations with the need for power production.

We believe that the most important knowledge gap to fill prior to development of an environmental design handbook for reservoirs is to develop tools that can assist balanced decisions between the environmental needs and the power production, similar to those already developed for the salmon handbook. The best way forward for environmental design in hydropower reservoirs is to establish a multidisciplinary research project, where scientists, power producers and managers can work together, focusing on one or two reservoirs in detail and use this as a pilot.

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Content

Foreword

This project was funded by Norwegian Environment Agency to NINA.

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This report was quality assured by Ola Ugedal and the responsible Research Director in NINA is Tonje Aronsen.

November 2019, Ingeborg Palm Helland

1 Introduction

1.1 The need for better mitigation measures in hydropower reservoirs

Norway has approximately 1200 lakes that are regulated for hydropower usage. Due to their ability to store large amounts of water, these reservoirs are the supporting beam in the Norwegian hydropower system, which consists of more than 1600 hydropower plants and makes up 96 % of the national power production[1]. Many of the Norwegian hydropower reservoirs are natural lakes turned into reservoirs when the hydropower dam was created, hence they contain natural ecosystems with local species. The most obvious effect of hydropower on affected lakes (reservoirs) is a change from natural water level fluctuations to regulated water levels, see example in Figure 1. The unnatural water level fluctuations cause changes in the physical and chemical properties of the reservoir, e.g. temperature, ice-cover, erosion, resuspension of nutrients and mixing of water, which in turn impact the living conditions for lake organisms (Brodtkorb 2000, Hirsch *et al*. 2017). The ability to manipulate water levels in reservoirs in a flexible way allows the power producers to regulate production according to market prices, which is very important for industry profit maximization.

The present environmental regulations for reservoir operations in Norway are predominantly based on limiting the maximum and minimum water level without any consideration of how rapidly or frequently the water level fluctuates within these limits. The limits are usually denoted HRWL (highest regulated water level) and LRWL (lowest regulated water level) and are given in the licence to the power company. Reservoir operational regimes typically follow a seasonal pattern, gradually increasing water level during late spring/early summer and decreasing water level during winter (see black curve in Figure 1). The pattern results from storing the spring and summer water surplus for increased production during winter, when the demand, prices and thus production profitability are highest. Recent studies have predicted that future operational regimes may lead to changes in the yearly, seasonal and daily regulations of the water levels in Norwegian reservoirs, as power producers rapidly adjust production levels to meet periods of peak demand or backstop shortfalls in supply (Charmasson *et al*. 2018). In fact, many Norwegian reservoirs are already experiencing frequent water level regulations (see blue curve in Figure 1).

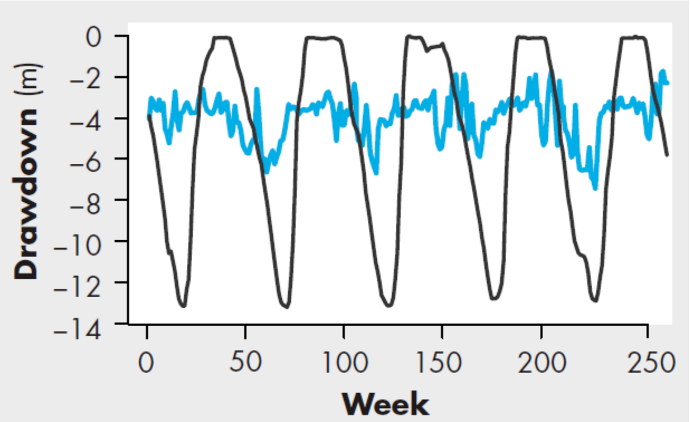

Figure 1. Example of two contrasting water level fluctuation curves in Norwegian reservoirs. Figure from Charmasson et al. 2018.

Despite the large number of hydropower reservoirs, there is relatively little public awareness of environmental impacts in lakes regulated for hydropower. This contrasts with the strong public concerns about regulated salmon rivers, probably due to the cultural and economic value of Atlantic salmon (*Salmo salar* L., hereafter salmon). Being a large hydropower country with numerous regulated salmon rivers, Norway has over decades developed strong research groups within hydrology, hydropower engineering and salmon biology, and in 2013, the "*Handbook for environmental design in regulated salmon rivers*" was published (Forseth and Harby 2013[2]). This handbook has become an important tool for local and national authorities as well as hydropower

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[1] https://www.nve.no/energiforsyning/energiforsyningsdata/om-magasinstatistikken/ (03.05.19)

[2] For English version see Harby and Forseth 2014

companies in Norway, seeking to balance power production with protecting viable salmon populations. Based on the success of the concept of environmental design, it is interesting to investigate the feasibility of developing a handbook for environmental design related to fish in reservoirs, similar to the one for salmon rivers.

The first question to ask when starting to develop environmental design for hydropower reservoirs is what the aim of such a handbook should be. It is clearly desirable to find ways to mitigate negative impacts on reservoir ecosystems without having a significant negative impact on the power production. However, it is not obvious what the management target of the mitigation measures should be. Is the aim to achieve good ecological conditions compared to how the natural ecosystem would be without the impact from hydropower? Or is the aim to secure that the fish population in the reservoir is harvestable and thus of value for locals and tourists through recreation and angling? The first aim would be in accordance with the goals of the EU Water Framework Directive, that Norway has implemented in the national legislation *vannforskriften*, which is to achieve *good ecological status* in all waterbodies. However, the latter aim is more in accordance with the traditional management of hydropower reservoirs in Norway and in accordance with the environmental design in salmon rivers. In salmon rivers, the management target is to achieve a harvestable surplus of salmon and the handbook for environmental design is a tool to achieve this while simultaneously securing profitable hydropower production. Historically, the most common approach to improve environmental conditions in reservoirs in Norway has been fish stocking, often regarded as a compensation to the local communities to ensure good harvesting possibilities despite potential negative impacts from hydropower. Before one looks for possible mitigation measures in reservoirs, it is important to define if the aim is to simply have viable and self-recruiting fish populations, or if the aim is to have fish populations that contain enough fish of desirable sizes for harvesting. Fish in lakes asses to have "*good ecological status*" may not always be interesting for angling.

In addition to *vannforskriften*, another ongoing process in Norway may influence the environmental mitigation in reservoirs, namely the revision of terms of the hydropower licenses. The main goal of the revisions is to improve the environmental conditions in lakes and rivers impacted by hydropower. The licenses themselves are not up for revision, meaning that HRWL and LRWL will not be revised, but the operational regime within HRLW and LRWL can be revised. The terms of more than 400 licenses can come up for revision before 2022, and presently 45 are ongoing and only 9 have been completed[3]. In the completed cases there were discussions whether the operational regime in the reservoirs should be modified, but this was mainly justified with social aspects like recreational use (e.g. boating, erosion, landscape), and not with the aim to improve the ecological conditions *per se* (Köhler *et al*. 2019).

According to *vannforskriften*, lakes and rivers that cannot meet the standard environmental target *good ecological status* due to strong physical alterations by humans (e.g. changes in size, discharge, form and shape) are designated as *heavily modified waterbodies* (HMWB). Many hydropower reservoirs fall into this category, which means that their environmental target will be to attain *good ecological potential* (GEP). GEP is defined as the best ecological conditions that can be achieved whilst still allowing human activities to continue. Presently, 968 lakes in Norway are designated as HMWB due to hydropower operations[4].

According to the Norwegian guidelines, GEP is to be set based on "the sum of all existing and new realistic measures" (Anonymous 2014). A crucial point in this process, called *tiltaksmetoden* in Norwegian, is to identify realistic mitigation measures that will result in a functioning ecosystem, based on whether each of the potential measures

i) are technically and economically feasible
ii) will not have a significant negative impact on the power production
iii) will not have a significant negative impact on the environment
iv) will realistically improve the ecological conditions

When dealing with reservoirs, identification of "realistic" mitigation measures is not straightforward, since it is only possible if one can predict with some certainty if a potential mitigation measure will have the desired effect on the ecosystem. We suspect that today's knowledge does not allow for such predictions, due to lack of

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[3] https://www.nve.no/konsesjonssaker, 25.05.19

[4] Data downloaded from https://www.vann-nett.no/portal/ 25.04.19

systematic work with testing and evaluation of mitigation measures for hydropower reservoirs. However, we believe that the concept of environmental design is a useful approach that could improve environmental conditions in Norwegian hydropower reservoirs in the years to come. To achieve this, we must start collecting and characterizing both ecological and hydrological data in reservoirs in a systematic way and combine it with knowledge of hydropower systems and production.

As awareness of the negative effects of fish stocking has increased, the Norwegian Environment Agency has stressed the need to focus on how to improve natural fish reproduction and avoid stocking (Anonymous 2017). Hence, there is an increasing need to identify and test alternative mitigation measures for sustaining reservoir fish production. According to a report published by The Norwegian Water Resources and Energy Directorate (NVE) (Glover *et al*. 2012), potential alternative mitigation measures for reservoirs are:

i) liming and fertilization (i.e. addition of Ca, N or P)
ii) water level restrictions
iii) habitat restoration (e.g. creation of smaller pools, addition of spawning gravel)

Fertilization is associated with risks of unintended ecological changes in the full watershed. Hence, the most promising mitigation measures are the hydrological (i.e. water level restrictions) and the habitat measures. This is in accordance with the handbook of environmental design in regulated salmon rivers, which highlights that hydrological measures and habitat measures should be used in combination to achieve the best results (Forseth and Harby 2013). Since hydrological measures can influence power production, it is important to balance the environmental gain against any potential power production loss or other type of socio-economic loss, such as the reservoirs' function in flood control. This is the strength of using the concept of environmental design, which seeks to evaluate, develop and implement measures to improve ecological conditions while considering the socio-economic value of hydropower production.

1.2 The concept of environmental design of hydropower

The concept of environmental design in regulated salmon rivers is based on two main parts, as illustrated in Figure 2. The first phase is about how to develop a ***diagnosis***, and the second phase identifies the suitable ***design solutions***. The handbook contains specific descriptions of methods used both in the diagnosis phase and for the design solutions. When setting the diagnosis, one starts with collecting data for habitat conditions, hydrology, salmon populations and the power production system. These data are used in a specific classification system described in the handbook, where the aim is to identify and rank the bottlenecks for salmon production. The bottlenecks that make the salmon population less viable are either habitat restrictions (e.g. lack of available spawning gravel for mature fish and/or shelter for juvenile fish) or hydrological restrictions (e.g. drying of preferred habitat or lack of flooding to attract migrating fish). When the diagnosis is set for a river, the search for the design solutions with largest effect can begin. For the habitat bottlenecks, one can implement habitat-related measures (e.g. addition of spawning gravel), whereas for the hydrological bottlenecks, it is important to find the best "water use" for the river. By modifying flow and water temperature, the aim is to use the water at the time and place where it is most needed and has a suitable temperature for salmon. Here, it is important to balance the need for water by the different life stages of salmon with the need for water for power production. Sometimes the power production must be somewhat reduced to secure a viable salmon population, but in some cases it is possible to optimise the water use for salmon without substantial negative impacts on the power production. In the handbook, tools for designing the optimal water use in combination with the relevant habitat measures are described.

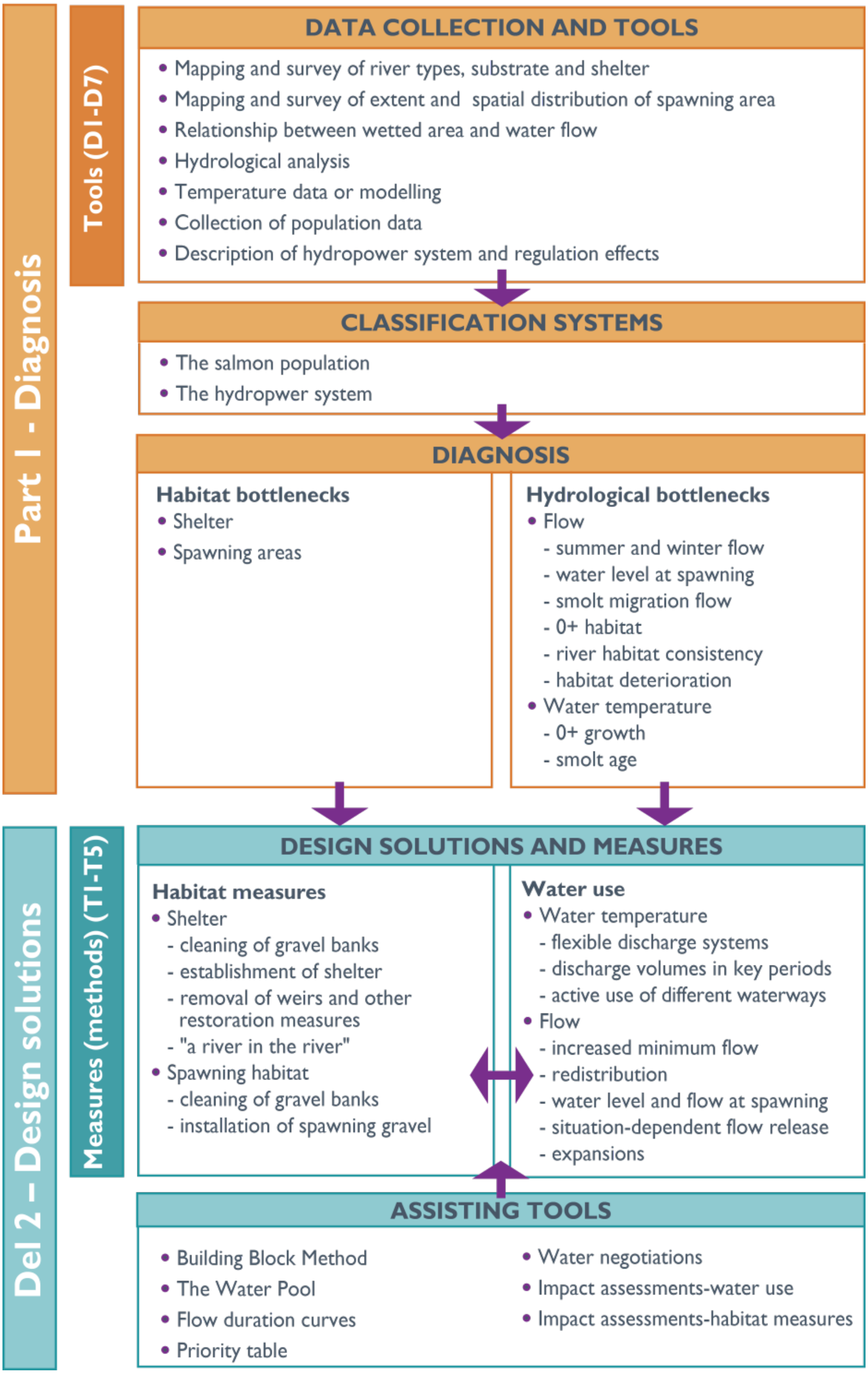

Figure 2. The tools and measures of environmental design for regulated salmon rivers. Figure from Harby and Forseth 2014.

1.3 The structure of this report

The aim of this report is to investigate the feasibility of developing a handbook for environmental design related to fish in reservoirs, similar to the one for salmon rivers. The report is a result of a project funded by Norwegian Environment Agency to NINA. The project has not contained any new field work or new analyses of biological or hydrological data. Rather the report builds on existing knowledge, partly based on available literature, but to a large extent based on expert opinions from scientists working on fish ecology in hydropower reservoirs, and discussions with environmental managers at the Norwegian County Governors. Hydropower producers or scientists working on hydropower technology or production modelling have not been included in this project, hence, this report should not be seen as a result of a full environmental design approach. Rather, this report is a first step towards method development for environmental design for reservoirs, which hopefully will ultimately lead to a full environmental design project.

The report consists of four more chapters after this introduction. **Chapter 2** summarizes the most important abiotic and biotic aspects of Norwegian hydropower reservoirs, aiming to show how the environmental effects of hydropower may vary between different types of reservoirs. The chapter is mainly based on literature and expert judgment, but also on available data from NVE and NINA. While the chapter starts with a broad perspective, covering all reservoirs in Norway, we try to narrow the scope in the end of the chapter and highlight which reservoirs types should be the focus for a future handbook of environmental design. **Chapter 3** focuses on the diagnosis phase. Here, we identify which available methodology and tools can be used to set the diagnosis in a hydropower reservoir. The content in the three first chapters is partly based on the outcome of a one-day workshop where national experts on environmental impacts of hydropower were invited, including scientist from NINA, SINTEF Energy, NTNU and UiO. **Chapter 4** focuses on potential design solutions. The chapter is mainly based on a survey among all County Governors to map which mitigation measures have been implemented in Norwegian reservoirs up until today. Finally, in **Chapter 5**, we summarize the main findings and give our recommendations for the steps in developing a handbook for environmental design in hydropower reservoirs.

2 Main abiotic and biotic aspects of hydropower reservoirs

2.1 Variation among Norwegian reservoirs

Hydropower reservoirs in Norway are highly variable. They range in e.g. size, depth, climate (i.e., altitude and latitude), fish community composition, geology, time since dam construction, connectivity and in the way and magnitude of how water levels are regulated (Figure 3, based on data from NVE[5]). Often the reservoirs are part of a larger power production system with many interconnectors, tunnels and pumps moving water between regulated lakes and rivers. These factors, in turn, determine the ecosystems' responses and vulnerability to hydropower operations. In this chapter, we describe the main abiotic and biotic properties of Norwegian reservoirs and the expected mechanisms behind how different types of reservoirs may vary in their vulnerability to hydropower impacts.

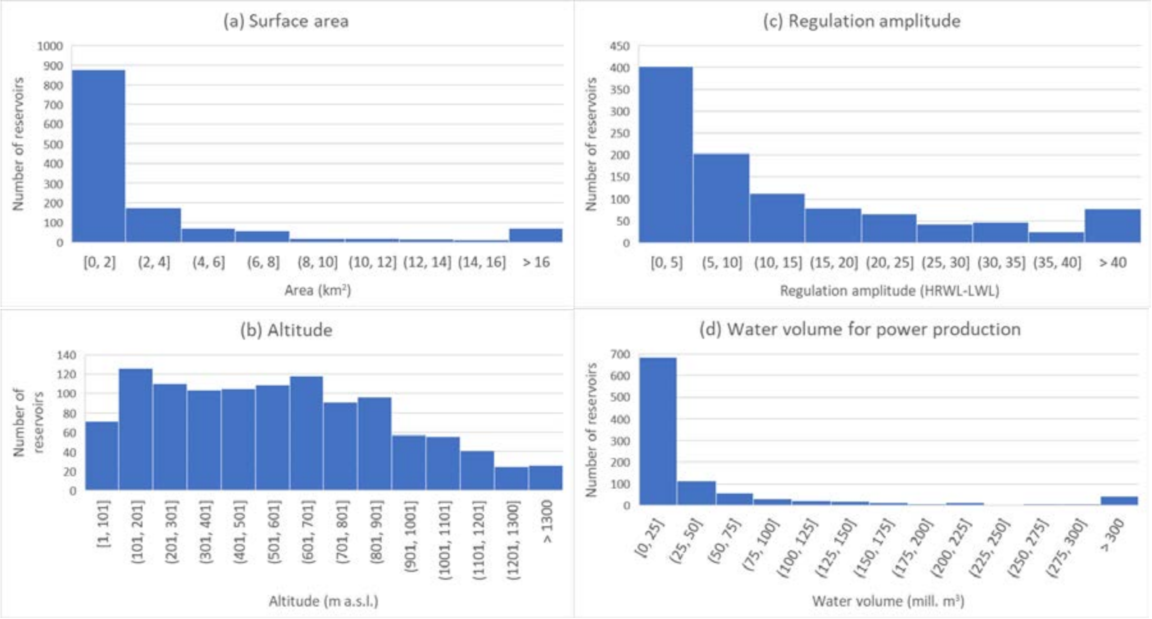

Figure 3. Distribution of (a) surface area (N=1331), (b) altitude (N=1136), (c) regulation amplitude (N=1051) and (d) water volume for power production (N=1018) of hydropower reservoirs in the NVE database[5].

2.2 Morphometry, geology and water quality

Morphometry determines key ecosystem processes in lakes and reservoirs (e.g. carbon and nutrient cycles, temperature conditions, community composition), as well as their vulnerability to anthropogenic impacts. Large and deep lakes typically have shorter ice-cover period and show less extreme water temperature fluctuations, they provide extensive habitats for pelagic biota (phyto- and zooplankton and planktivorous fish), they host more diverse communities, and are generally more resistant to human impacts due to their large volume and variable habitats. Small and shallow lakes are, in contrast, exposed to larger temperature fluctuations and longer ice-cover period, dominated by littoral benthic biota and/or fuelled by terrestrial (allochthonous) sources of carbon and nutrients, and are more vulnerable to human disturbance such as pollution, water level regulation, species' introductions and harvesting of fish stocks. Therefore, morphometry (area, depth and shoreline complexity) is a key factor to consider in management and mitigation of environmental impacts in hydropower reservoirs.

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[5] Database on the hydropower system, developed and not developed https://register.geonorge.no/geodatalov-statusregister/vannkraft-utbygd-og-ikke-utbygd/f587a15a-c72a-4b21-aae9-4132df1bdd27

The reservoirs' area, depth, bottom profile and shoreline complexity are largely determined by their location (e.g. latitude and altitude) and geology. Most large reservoirs in Norway are located at low altitudes and latitudes, including many deep and narrow "fjord-lakes" like Suldalsvatnet (Rogaland). In these reservoirs with steep slopes and relatively simple shorelines, relatively small bottom areas are exposed to drying and freezing following water level drawdown. However, most reservoirs in Norway are relatively small (< 2 km^2, see Figure 3). These small reservoirs, as well as larger but relatively shallow reservoirs with complex shoreline, are more heavily impacted by water level drawdown and subsequent drying and freezing of large bottom areas, as can be seen in the aerial photographs from Gyvatn in Otra watercourse, southern Norway (Figure 4). Besides reducing reservoir surface area and volume, water level drawdown in shallow and reticulate reservoirs may lead to formation of new "islands" and separate basins that can have distinct abiotic and biotic characteristics (Figure 4).

Geology is another fundamental abiotic factor affecting reservoirs' water quality and vulnerability to water regulation impacts. Reservoirs surrounded by and/or formed on loose substrate are more susceptible to regulation-induced changes in water quality (i.e., turbidity, colour and nutrient concentrations) than reservoirs on barren bedrock. Moreover, reservoirs with rocky bottom also provide better spawning and nursing habitats for resident salmonid populations than reservoirs with loose bottom substrate. The latter reservoirs are generally more eutrophic and situated in warmer climate and thus often host non-salmonid fishes that prefer vegetated littoral habitats and soft bottom substrate.

Water quality and temperature in connected reservoirs, lakes and rivers depend largely on from which depth water is released into a tunnel or downstream river, and to which depth it is released in the downstream water body. Seasonal changes in water temperature and quality are important aspects in evaluation and monitoring of the abiotic status of reservoirs. In some cases, reservoir water quality is determined by a match/mismatch between water level and wave action; particularly high resuspension of sediment (consisting of silt, detritus, nutrients and pollutants) can be expected when strong winds occur at low water levels. An example is Govdajavri (Storfjord, Troms), with large between-year differences in water turbidity (Figure 4).

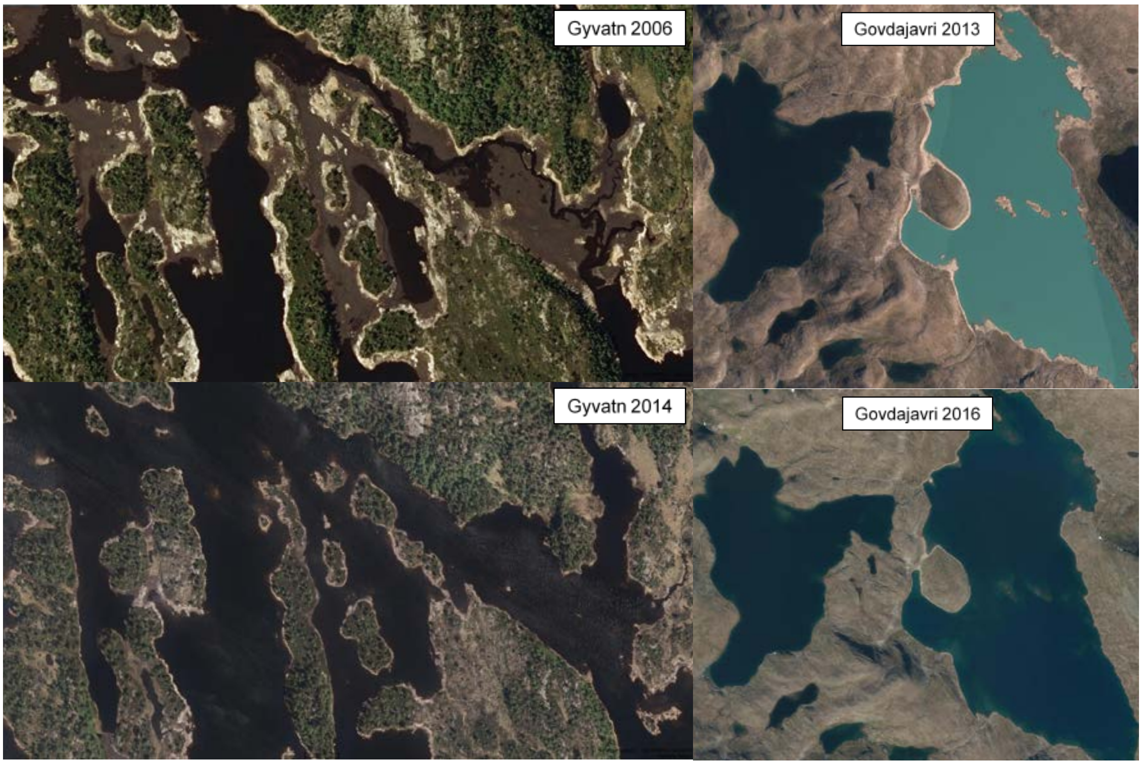


Figure 4. Aerial photographs showing Gyvatn (area 4.49 km^2, regulation amplitude 3 m) at low (2006) and high (2014) water level (left), and Govdajavri (area 1.10 and 4.02 km^2, regulation amplitude 24 m) in turbid (2014) and clear (2016) water stage (right). Aerial photographs obtained from www.kart.finn.no.

2.3 Connectivity

Dams in hydropower systems affect hydro-morphological processes in lakes and rivers. By creating physical barriers and hindering downstream transport of vital substrate, carbon and nutrient resources, dams typically reduce quantity and quality of suitable habitats for riverine biota. In addition, water level drawdown in reservoirs may prevent migration of fish and other biota to connected rivers (Figure 5) and reduce exchange of nutrients and carbon between aquatic and terrestrial ecosystems. Hence, decreased connectivity in hydropower systems may have far-reaching impacts on connected ecosystems. Lack of connectivity is particularly problematic for species that need to migrate between various habitats or ecosystems to complete their life cycles and/or to survive through seasonal environmental fluctuations.

Connectivity between a reservoir and other lakes, reservoirs, up- and downstream river systems, as well as to the riparian areas surrounding the reservoir, is a key property to consider in reservoir management and monitoring. As discussed more in section 2.6., reservoirs located in different parts of a hydropower production system are very differently affected by water inflows and outflows between connected systems. Reservoirs in the middle parts of power production systems, often located at intermediate altitudes, typically have the most complex connections to other waterbodies. Therefore, these ecosystems are among the most challenging targets for monitoring and mitigation actions; they are heavily impacted by inflows (of water, nutrients, organisms, pollutants etc.) from upstream systems and they affect water quantity and quality in downstream systems via (semi-)natural streams and rivers and man-made tunnels (Figure 6). In contrast, “source” reservoirs at the highest altitudes in the hydropower system are not subjected to human-induced changes in water inflows, but they are affected by hydropower-induced water level regulation and affect water quantity and quality in downstream waterbodies.

Figure 5. Aerial photographs showing the delta area of inlet streams at Tesse (Lom, Oppland; area 12.84 km^2, regulation amplitude ca.12 m) at low (2011) and high (2015) water level. Aerial photographs obtained from www.norgeibilder.no.

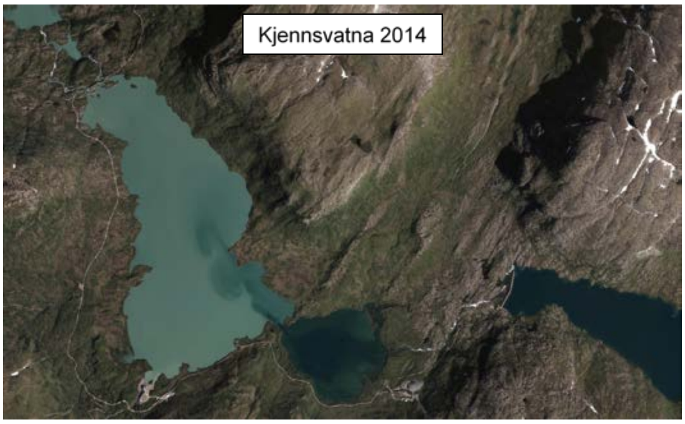


Figure 6. Release of turbid water through a turbine tunnel (lower left corner) reduces water quality in Vestre Kjennsvatnet (Hemnes, Nordland) and in the downstream rivers and ponds, whereas water remains clear in upstream Austre Kjennsvatnet and Gresvatnet. Aerial photograph obtained from www.norgeibilder.no.

2.4 Biological productivity

The abovementioned abiotic characteristics are key determinants of biological productivity in hydropower reservoirs. For instance, lake area, depth, bottom profile and shoreline complexity affect the relative contributions of littoral and pelagic zones to the reservoir total area. Small, shallow, gentle-slope and reticulate lakes and reservoirs are generally dominated by littoral zone and biota, including benthic algae, macrophytes, invertebrates, and benthivorous fish species and fish life stages. In contrast, large, deep, steep-slope and circular lakes and reservoirs consist mainly of open-water pelagic zone and biota, including phyto- and zooplankton and planktivorous fish species and fish life stages. Water quality (i.e., turbidity, colour and nutrient concentration), in turn, determines at which depth there is still enough solar radiation to support photosynthesis by littoral (benthic algae and macrophytes) and pelagic (phytoplankton) primary producers. Hence, morphometry and water quality are key factors affecting the amount and relative contributions of littoral and pelagic biological productivity in reservoirs.

Besides littoral and pelagic (i.e., autochthonous) production, reservoir biota are to various degrees subsidized by terrestrial (i.e., allochthonous) carbon and nutrient sources. This is particularly the case in reservoirs surrounded by abundant vegetation or subjected to substantial inflow of humic water from the catchment. Terrestrial food resources (e.g. adult and larval stages of insects) can be a major dietary subsidy for reservoir fishes especially if the littoral zone is heavily impacted by water level regulation. However, input of terrestrial inorganic and organic matter does not always mean improved reservoir productivity; humic (brownish) water increases light attenuation and thereby limits the extent of within-lake littoral and pelagic production, as well as reduces feeding efficiency of fish (Karlsson *et al*. 2009). Moreover, high input of terrestrial organic matter may make reservoir bottom substrate a suboptimal habitat for feeding and reproduction of fish and invertebrates. The same applies to reservoirs that are subjected to inputs of turbid water from melting glaciers. Such reservoirs are commonly considered very unproductive, due to the narrow euphotic zone causing limited primary production in the littoral and pelagic zones and suboptimal bottom substrate dominated by fine silt.

In addition to morphometry and water quality, biological productivity in reservoirs is strongly affected by the direct and interactive effects of water level regulation. The aspects related to magnitude, timing, frequency and rate of water level regulation will be discussed more in Section 2.7. However, it should be noted here that water level regulation typically affects reservoir abiotic characteristics, such as morphometry, water quality and connectivity, with direct and indirect impacts on biota in the reservoir littoral, pelagic and deep profundal zones, as well as on terrestrial biota living near the reservoir shores. Freezing, desiccation and increased erosion of shallow bottom areas typically increase direct mortality of reservoir biota, but also lead to decreased physical complexity of the littoral zone, thus providing limited shelter, substrate and habitat for benthic organisms. Indeed, the most evident and severe impacts of water level regulation occur in the reservoir littoral zone which is typically the most diverse and productive habitat in lakes (Strayer and Findlay 2010) and also providing key ecosystem services for the society.

2.5 Fish community composition

As described earlier, lake abiotic characteristics largely define the availability and productivity of different habitats in lakes and reservoirs. This, together with connectivity and species' immigration history (including human translocation of fish), define the community composition and species' abundance (Figure 7). Due to harsh climatic conditions and geographical isolation, most lakes and reservoirs in Norway are relatively species-poor. At the same time, these ecosystems host cold-water adapted species, such as Arctic charr (*Salvelinus alpinus*).

Knowledge of community composition is essential for a sound evaluation and mitigation of hydropower impacts in reservoirs. Different species and life stages of species typically have contrasting habitat and water quality requirements, as well as varying sensitivities to competitive, predatory and anthropogenic impacts. For example, sessile biota, such as littoral benthic algae, macrophytes, molluscs and fish eggs and larvae, are generally more heavily exposed to regulation impacts than more mobile and pelagic taxa and life stages. Hence, knowing which species or taxa are, or should be, currently present in a reservoir is a necessity for securing vital populations of taxa that have a key role in the reservoir food web and ecosystem processes. Such taxa include primary producers providing energy for higher trophic levels, as well as important fish food resources such as large benthic and pelagic crustaceans (e.g. *Lepidurus arcticus*, *Gammarus lacustris* and *Mysis relicta*).

Regulated rivers and lakes in Norway are popular places for recreational fishing, and traditionally serval reservoirs were also important for commercial fisheries (see e.g. Hesthagen 2018 a,b). Therefore, the public attention and concern often focuses on hydropower impacts on river and reservoir fish stocks. Brown trout (*Salmo trutta*) and Arctic charr are the most popular and common fish species in Norwegian reservoirs. Both species spawn in autumn and prefer relatively cold, clear and oligotrophic water. However, they show some crucial differences in e.g. habitat preferences and life history strategies. Brown trout usually spawn in flowing waters. Thus, reservoir brown trout need to have access to good-quality riverine spawning habitats to complete their life cycle, and they also need to return after spawning to the reservoir to feed. Brown trout juveniles need suitable conditions to survive and grow in the spawning streams up to some years, and at some point, they need to migrate to the lake or reservoir to continue growing. Thus, connectivity, water and habitat quality, and hydro-morphological conditions in connected streams and rivers are key factors affecting brown trout recruitment success and population density in reservoirs. For adult brown trout, scarcity of profitable littoral food resources may strongly limit growth rate, survival and reproductive success.

Arctic charr is generally considered as a more flexible fish species than brown trout due to its ability to use littoral, pelagic and profundal habitat and food resources and to feed throughout the year. Arctic charr typically spawn within lakes and reservoirs and thus it does not need access to spawning streams. However, recruitment success of Arctic charr can be severely reduced due to regulation-induced freezing, desiccation, erosion and silting of spawning habitats within reservoirs. As is the case for brown trout, adult Arctic charr often show reduced growth rate, condition and/or abundance in reservoirs where large-sized, nutritious benthic prey items (e.g. *G. lacustris* and *L. arcticus*) have vanished due to water level regulation (Aass *et al*. 2004, Milbrink *et al*. 2011).

In many lakes, brown trout and Arctic charr coexist, and often charr is the subdominant species of the two. Brown trout is a more aggressive competitor for littoral resources and it can also predate heavily on small Arctic charr. Presence of small prey fish, such as minnow (*Phoxinus phoxinus*) or sticklebacks (*Pungitius pungitius* and *Gasterosteus aculeatus*), may facilitate early shift to piscivory and increased growth rate of brown trout, thereby also increasing predation pressure on larger prey fish like small Arctic charr. Predation by brown trout on small Arctic charr seem particularly common in winter-time when other food resources may become scarce (Amundsen and Knudsen 2009). Winter is also the period when water levels in many reservoirs decline. This, in turn, increases the encounter rate between predatory brown trout and small Arctic charr due to decreased reservoir volume and availability of shelter in the shallow areas.

These aspects are crucial for management of reservoir fish populations, in terms of exploitation of fish stocks and mitigation actions aiming to support natural recruitment. It should be noted that a simple mitigation measure, such as improved connectivity between reservoir and spawning streams, may benefit only a specific fish species or fish life stage, but be detrimental for others. For instance, improved recruitment success of brown trout may lead to increased negative competitive and predatory impacts on coexisting Arctic charr. Moreover, improved recruitment may increase brown trout population density in the reservoir to such a level that food resources for adult fish become very limited. In fact, the growth and condition of brown trout and Arctic charr are highly density-dependent, meaning that individuals typically grow faster and larger when the population density is relatively low (Amundsen *et al*. 2007). Therefore, some heavily regulated lakes can host scarce populations of large-growing "trophy" brown trout or Arctic charr because hydropower operations limit recruitment success and thereby keep population density low, leaving more food for surviving individuals.

The inter- and intra-specific competitive and predatory interactions between and within brown trout and Arctic charr populations are very complex, but should be given careful consideration in reservoir management. The situation becomes even more complex in reservoirs hosting relatively diverse fish communities, as is the case in large, low-land reservoirs in south-eastern Norway. Some of these lakes host abundant pelagic populations of small planktivorous fishes, such as whitefish (*Coregonus lavaretus*), vendace (*Coregonus albula*) and/or smelt (*Osmerus eperlanus*). Similar to Arctic charr, these fishes spawn within lakes and reservoirs in autumn or spring (smelt), but their preferred pelagic habitat and food (zooplankton) resources are generally less heavily impacted by water level regulation. These species are often among the main prey of large predatory brown trout, as is the case in the reservoirs Storsjøen (Hedmark county) (Eloranta *et al*. 2019) and Mjøsa (Hedmark, Oppland and Akershus county) (data from "Fisk i store innsjøer" project, NINA, in prep.). Similar to some other large reservoirs in southern Norway, Mjøsa hosts spring-spawning cyprinid and percid fish species that often prefer littoral resources. These species have very different habitat and water quality requirements than brown trout and Arctic charr, but they still do partly compete for the same food and habitat resources.

Magnitude and seasonal pattern of water level regulation likely has contrasting impacts on autumn- and spring-spawning fishes; eggs and larvae of autumn-spawners need to stay watered and viable throughout the winter, whereas spring-spawners may show high egg survival but high juvenile mortality due to limited growth and/or high predation pressure. Therefore, how water levels are regulated in a reservoir may ultimately affect recruitment success and population density and thereby competitive and predatory interactions between salmonid and non-salmonid fish species.

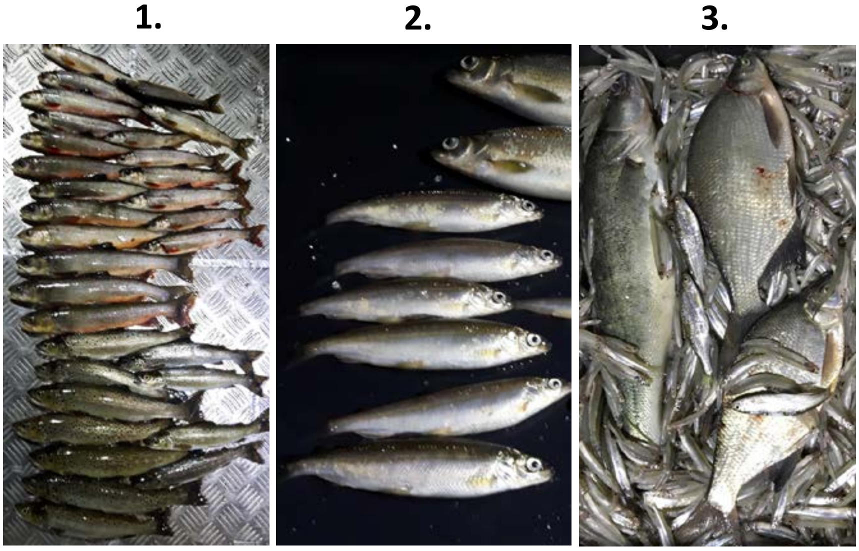


Figure 7. Examples of pelagic fish communities in Norwegian lakes and reservoirs. Most Norwegian lakes host populations of brown trout and/or Arctic charr (1), but some large lakes have abundant populations of small pelagic whitefish (2) and/or smelt (3). The fish were caught with a pelagic pair-trawl during the field work in "Fisk i store innsjøer" project led by NINA.

2.6 The role of reservoirs in the hydropower system

In this paragraph, we describe some general patterns related to the location and role of reservoirs within hydropower systems. We do not, however, discuss the importance of reservoirs for power generation and profitability as we have limited knowledge and competence on this matter. While this report is written by scientists with a main expertise in fish ecology, we emphasize the need for a close dialogue between experts within ecology, hydrology and power production operations when the suggested future handbook for environmental design in hydropower reservoirs is to be developed. This is crucial in order to find the best win-win design solutions, i.e. mitigation measures that improve ecological and socio-economic status of reservoirs without significant economic and energy loss.

Each waterbody has its own role in the power production system and, as described earlier, shows site-specific responses to hydropower operations depending on prevailing abiotic and biotic conditions. Headwater reservoirs situated at high altitudes usually function as water storages and they have high power production capacity due to high head. Such reservoirs are commonly subjected to gradual water level drawdown during winter and spring, followed by reservoir filling during the snow-melt period in late spring and early summer. These mountain reservoirs typically have the largest regulation amplitudes (difference between HRWL and LRWL). At the same time, they are rather isolated and unproductive ecosystems with species-poor communities. In many cases, there is relatively little human activity in the surrounding areas of such reservoirs, but in other cases such reservoirs are located in mountain areas frequently used for recreation and close to numerous cabins or holiday houses.

The reservoirs at mid-altitudes are often connected to both up- and downstream reservoirs, lakes and rivers. Therefore, these ecosystems are exposed to complex inflows and outflows of water of variable quantity and quality. The complex water flows and hydropower operations in mid-altitude reservoirs are often reflected to frequent and irregular water level fluctuations (Figure 8). Regardless of location, similar rapid water level fluctuations can be observed in reservoirs of small volume (i.e., area and/or depth), because such waterbodies are inherently sensitive to natural variation in weather conditions (i.e., water inflows and outflows).

Reservoirs located at the downstream end of hydropower systems often have relatively large area and volume and are therefore less sensitive to natural and anthropogenic water level fluctuations. Despite low head and relatively small regulation amplitude, these reservoirs have substantial power production capacity due to the large volume of regulated water. These reservoirs are commonly located in more populated areas and host more diverse biota than high-altitude reservoirs. These reservoirs, and particularly their outlet dams, also gain much public attention due to potential negative impacts on migratory fish in downstream rivers, including Atlantic salmon sea trout and eel (*Anguilla anguilla*). Impacts of hydropower operations and damming on these highly valued fish species are generally more “burning issues” for the general public and management authorities. This illustrates a common challenge in management of hydropower systems; while keeping water level relatively stable in reservoirs could support establishment of a viable littoral zone and natural recruitment of resident fish, it may demand reduced discharge of water to downstream rivers, with potential detrimental impacts on these ecosystems and their fish stocks. Hence, as discussed in Section 3.6., holistic evaluation and sustainable management demands careful consideration of all connections between reservoirs, lakes and rivers within the hydropower system.

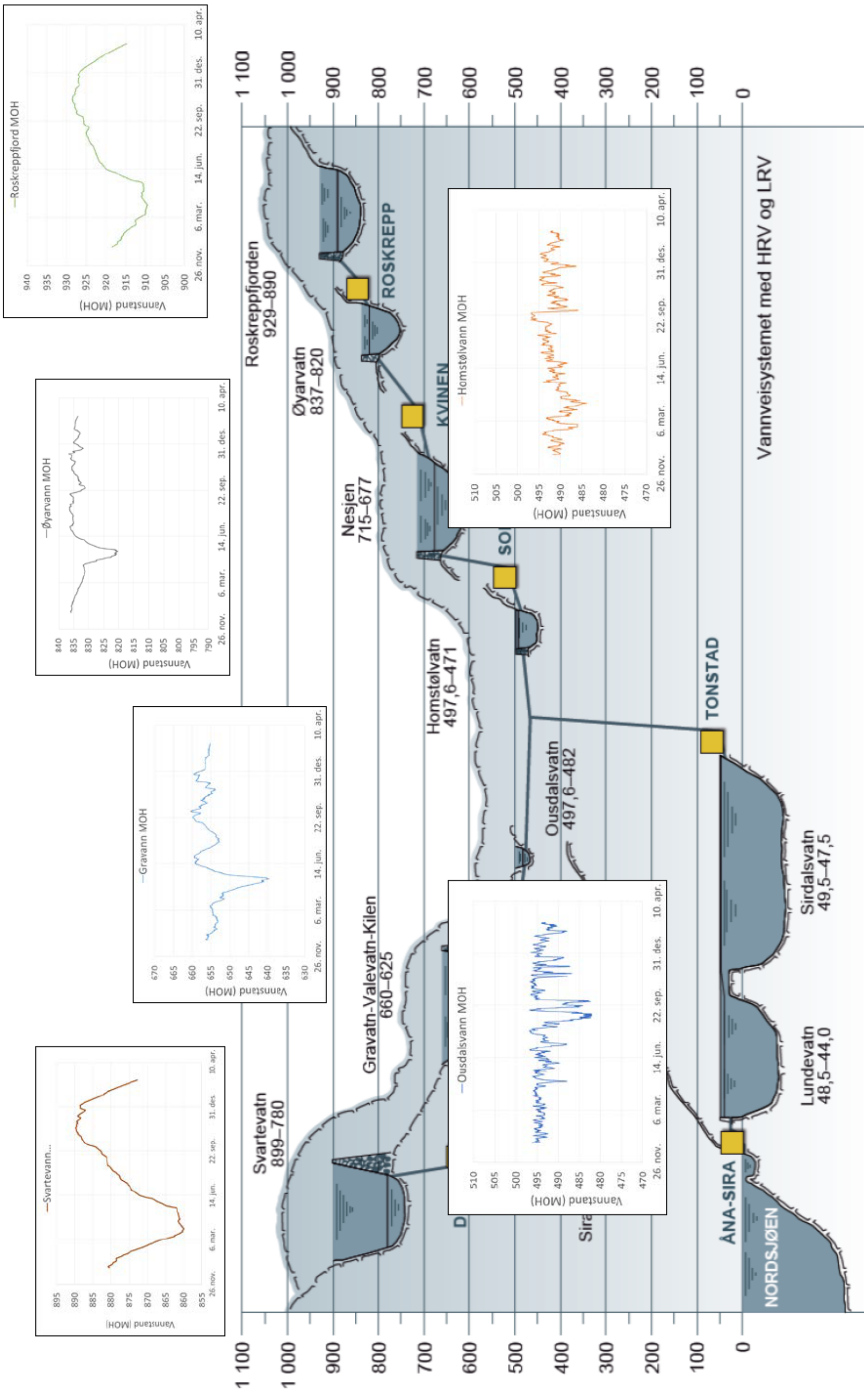


Figure 8. Dependence of water level regulation pattern on reservoir's location, morphometry and role in the hydropower production system. Large high-altitude storage reservoirs typically show regular seasonal, high-amplitude water level regulation (see Svartevann and Roskreppfjorden), with winter and spring water level drawdown being followed by reservoir filling during ice-melt period in late spring and early summer. The smaller mid-altitude reservoirs are subjected to more frequent and irregular water level fluctuations, due to both complex water inflows and outflows between connected reservoirs and to their higher sensitivity to natural variation in weather conditions. The large low-land reservoirs typically show gradual seasonal, low-amplitude water level fluctuations. Besides limited production capacity due to low head, the low-land reservoirs typically have stronger restrictions for hydropower operations due to their location in more populated areas and potential negative impacts on migratory fish populations in the downstream river systems. Figure by J. Charmasson, SINTEF.

2.7 Patterns of water level fluctuations

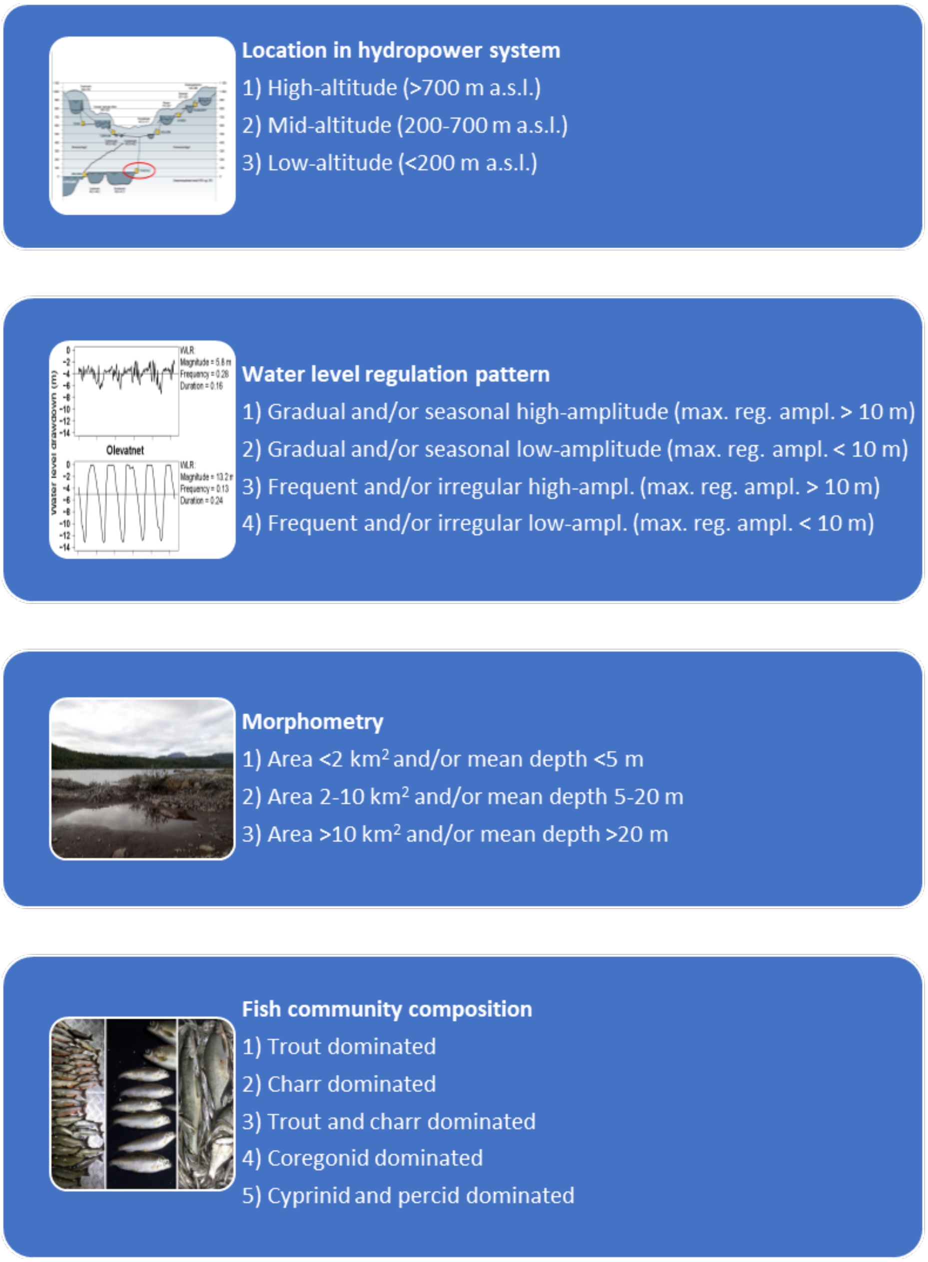
Reservoirs in Norway show very variable water level regulation patterns. As mentioned previously, this pattern is strongly dependent on the reservoir's morphometry and location in the hydropower system. Large and deep reservoirs typically show gradual water level fluctuations, whereas small and shallow reservoirs are subjected to more frequent and rapid water level fluctuations induced by both natural (i.e. weather conditions) and anthropogenic (i.e. hydropower operations) factors. At the same time, relatively large and deep reservoirs located in high-altitude mountain areas are typically subjected to high regulation amplitude, because they have high production capacity (high head) and provide water for downstream hydropower plants. The most restricted regulation amplitudes are typically found in large low-land reservoirs with low head, more densely populated surroundings, and often also supplying water to a downstream river system hosting valuable anadromous fish populations.

In Norway, hydropower producers have reservoir-specific restrictions for the maximum (HRWL) and minimum (LRWL) water level. In some cases, reservoirs need to be filled before a given date in spring or early summer (e.g. 1st of June). This restriction is typically based on societal aspects (e.g. to meet requests from cabin owners or tourist industry) rather than ecological requirements. This means that hydropower companies are not faced with any restrictions on the frequency, speed and timing of water level regulations in reservoirs, as long as they stay within the prescribed limits for HRWL and LRWL. Although regulation amplitude largely defines the reservoir's area and volume and thereby also the amount of habitat available for aquatic biota and biological productivity, this metric alone cannot describe the total impact. In some cases, frequency, timing and rate of water level fluctuations can be equally, if not even more, important factors affecting the status of fish populations and natural processes in reservoir ecosystems. For instance, late reservoir filling in spring may delay the early development of key littoral invertebrate taxa such as *Lepidurus arcticus*, with potential subsequent negative impacts on their reproductive success and survival, as well as on food availability for fish (Rognerud and Brabrand 2010). Low water levels in critical breeding and migration periods may also limit reproductive success and survival of both spring- and autumn-spawning fishes. Frequent and rapid water level regulation increases physiological stress and may lead to increased direct mortality (stranding) of immobile taxa and life stages, including aquatic plants, molluscs and juvenile fish. Frequent and rapid water level fluctuations may in some cases increase food and nutrient availability via increased drift of prey and sediment resuspension. In the long-term, however, such water level regulation may have negative impacts on water quality and reduce the overall ecosystem productivity. Hence, there is a need to develop more metrics for the effects of water level regulations in reservoirs, as the commonly used amplitude only describes a limited part of the impact.

While hydropower companies and environmental authorities in Norway know the volume of water in each reservoir that can be used for power production, it is often not known how large proportion this water comprises of the total lake volume, simply because bathymetric (depth) maps are missing from most reservoirs. Without proper bathymetric maps, it is practically impossible to evaluate the extent of bottom areas exposed to drying, freezing and erosion during low water level periods. In addition, without proper data of water quality (at least as measured by Secchi depth), it is tricky to evaluate the extent (depth and area) of the reservoir's productive (littoral and pelagic) zone and how much of this zone is lost due to water level regulation. Hence, we argue that improved knowledge of bathymetry, water quality and water level regulation impacts is urgently needed for more holistic evaluation and sustainable management of hydropower reservoirs in Norway.

2.8 Narrowing the scope for a handbook

Given the large variation among Norwegian hydropower reservoirs, it is not realistic to create a handbook for environmental design that will be useful for all reservoir types. Hence, it would be useful to narrow the scope and identify some reservoirs that are of particular interest and start with method development targeting these reservoirs. Based on the main abiotic and biotic characteristics described above, one could conceptually categorize all reservoirs according to different classes, as we have sketched in Figure 9. We do not propose to use and combine all these classes simultaneously, because some combinations are not possible (e.g. cyprinids and percids do not exist in high altitude lakes) and the total number of combinations would be very high. Further, the classes we have used are for illustrational purposes only and neither the classes nor the class boundaries have been scientifically tested, they are simply used as examples of parameters assumed to be of relevance to describe reservoir ecosystems. Hence, rather than a suggestion for a specific categorization system, Figure 9 can be seen as a conceptual approach to how one could identify what type of reservoirs are most common, or most interesting to focus on, before creating a first handbook for environmental design for hydropower reservoirs. Several other aspects could be added to the suggested classes; in particular, it would be an interesting exercise to include socio-economic valuation before identifying key reservoirs. Here, several metrics could be used, such as the reservoir's economic value for hydropower production, importance for flood protection, recreational use and presence of priority species (not only fish). Given that the authors of this report have their expertise in limnology and fish ecology and lack expertise in socio-economic valuation, these aspects have not been elaborated further for the time being.



Location in hydropower system
1) High-altitude (>700 m a.s.l.)
2) Mid-altitude (200-700 m a.s.l.)
3) Low-altitude (<200 m a.s.l.)

Water level regulation pattern
1) Gradual and/or seasonal high-amplitude (max. reg. ampl. > 10 m)
2) Gradual and/or seasonal low-amplitude (max. reg. ampl. < 10 m)
3) Frequent and/or irregular high-ampl. (max. reg. ampl. > 10 m)
4) Frequent and/or irregular low-ampl. (max. reg. ampl. < 10 m)

Morphometry
1) Area <2 km^2 and/or mean depth <5 m
2) Area 2-10 km^2 and/or mean depth 5-20 m
3) Area >10 km^2 and/or mean depth >20 m

Fish community composition
1) Trout dominated
2) Charr dominated
3) Trout and charr dominated
4) Coregonid dominated
5) Cyprinid and percid dominated

Figure 9. Suggested examples of classes describing some important abiotic, biotic and hydropower-related characteristics for Norwegian hydropower reservoir. The list is just an illustration of a conceptual way of defining different reservoir types and should not be understood as a final suggestion for a categorization system for Norwegian hydropower reservoirs.

We do not have access to data that can be used to group all reservoirs into the different classes we have shown in Figure 9 (we lack information on e.g. regulation pattern and depth). However, based on available data from NVE[5], we have counted the number of reservoirs in each class based on area, altitude and regulation amplitude (Table 1). This shows that from the 998 reservoirs with available data, the majority are smaller than 2 km^2 and situated at mid-altitude (200–700 m a.s.l.). Almost half of the reservoirs (46 %) have regulation amplitude above 10 m (466 vs 532 below).

Table 1. Number of hydropower reservoirs in different classes, based on altitude, surface area and regulation amplitude.

		Area			
	Reg. amplitude	< 2 km^2	2-10 km^2	> 10 km^2	*sum*
< 200 m a.s.l.	< 10 m	59	42	34	*135*
	> 10 m	17	8	-	*25*
200-700 m a.s.l.	<10 m	204	65	17	*286*
	> 10 m	105	83	23	*211*
> 700 m a.s.l.	< 10 m	81	25	5	*111*
	> 10 m	113	83	34	*230*
	sum	*579*	*306*	*113*	*998*

With regards to fish community, we do not have information on species composition in all reservoirs, but looking at the available data from the lake fish database at NINA[6], we see that we have information on fish occurence from 969 of the reservoirs in NVEs database. Of these 969 reservoirs, 91 % contain brown trout and 31 % charr (Figure 10). The third most commonly occurring species according to the database is minnow, present in 16 % of the reservoirs. The available data in the lake fish database are not necessarily reflecting the true species distribution and there may be a bias towards a high number of brown trout since many environmental monitoring projects have targeted this species, thus these data have been stored in the database. Further, not all species have the same catchability and some may therefore be underrepresented. Nevertheless, it is well known that brown trout is the most commonly occurring freshwater fish species in Norway. Given that brown trout and charr are most common in Norwegian reservoirs and also are among the species we have most knowledge about, we therefore concentrate on these two species in the remaining of this report. It is worth, however, to note that even though most reservoirs have less than five fish species (Figure 11), the highest number of species present in one reservoir is 25 (Øyern in Akershus/Østfold, regulation amplitude 2.4 m). Environmental design targeting brown trout and Arctic charr may not benefit these other species. Yet, we think it is reasonable if a first environmental design handbook for reservoirs focuses on brown trout, since this is the most feasible first step.

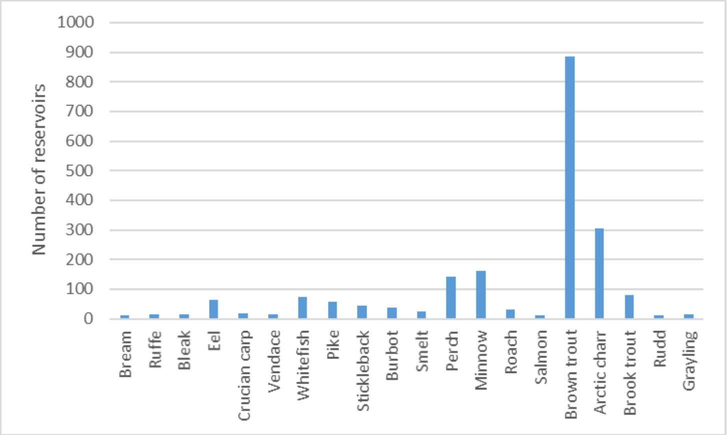


Figure 10. Presence of common fish species in Norwegian reservoirs according to NINA fish database[6].

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[6] Database on freshwater fish occurrence https://osf.io/xs97g/wiki/Data%20sources%20and%20structure/

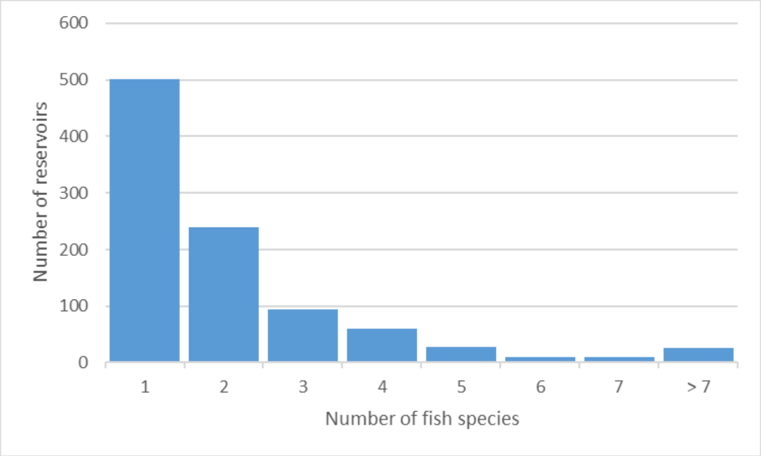

Figure 11. Number of fish species present in each hydropower reservoir in NINAs fish database[6].

3 Setting diagnosis in hydropower reservoirs

3.1 Known effects on fish in Norwegian reservoirs

Before a handbook for environmental design for fish in Norwegian reservoirs can be developed, it is necessary to know how to develop the diagnosis, i.e. to identify key bottlenecks for fish populations. Based on many years of fish monitoring in Norwegian reservoirs, several ecological bottlenecks are already known. Hirsch *et al*. (2017) recently made a literature review on how hydropower-induced water level fluctuations affect alpine lake ecosystems, from abiotic conditions to lower trophic levels and ultimately to fish. Here, we provide a short summary of some of the most relevant and well-known bottlenecks for fish in Norwegian reservoirs (summarized in Figure 12, from Hirsh *et al*. 2017).

It is a basic fact that water regulation will change the area and volume of the reservoir. While the available habitat for aquatic species is reduced when the water level is low, many reservoirs also have a larger volume than the original natural lake, because the increased water level following damming has flooded land areas. However, the largest impacts on the ecosystem likely result from unnatural water levels fluctuations. The littoral zone is particularly important for plants and animals in lakes, but in hydropower reservoirs water level fluctuations normally increase unnatural erosion, drying and freezing of these areas. For this reason, species like Arctic charr may have shifted from feeding in the littoral zone to feed in the open water pelagic areas as prey is no longer available in the littoral (Eloranta *et al*. 2016). For littoral-oriented species like brown trout, this is even more serious, as they are less able to utilize the pelagic food resources. Moreover, brown trout, which often spawn in smaller streams around the reservoir, may lose access to their spawning habitats if the water level is too low. Similarly, important shelter habitat for juvenile fish along the shore may be destroyed or become unavailable due to water level regulation (Hirsch *et al*. 2017). Although some bottlenecks are already known, such as lack of access to spawning habitats or reduced food availability, this knowledge needs to be systematized and properly tested to better understand under which circumstances and in what type of reservoirs the different bottlenecks occur. The literature review on alpine hydropower reservoirs by Hirsch *et al*. (2017) concluded that the mechanisms underpinning how reservoir ecosystems respond to water level regulation are complex and often case specific, and the same seems to hold for resident brown trout populations in Norwegian hydropower reservoirs (Eloranta *et al*. 2018).

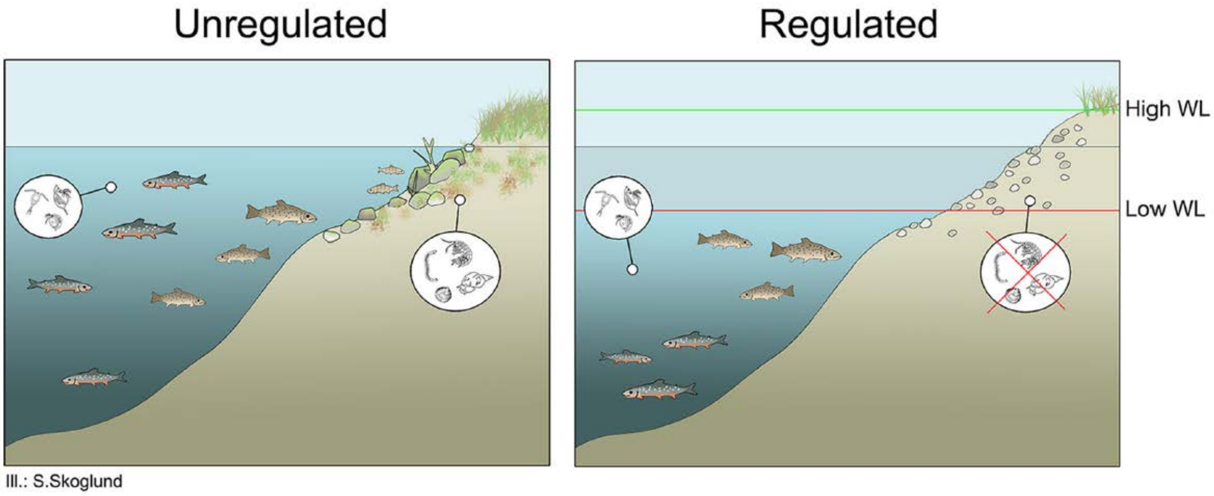

Figure 12. Illustration of main ecological processes in littoral zone of hydropower reservoirs. Figure from Hirsch et al. 2017.

Several Norwegian studies have shown lower fish densities and growth rates in hydropower reservoirs than in natural lakes, but there are also several examples of viable fish populations in reservoirs with large regulation amplitude (Aass *et al*.2004, Milbrink *et al*. 2011, Eloranta *et al*. 2018). This shows that water level fluctuations not always have a strong negative effect on fish. As seen from Figure 13, there is no systematic relationship between regulation amplitude and fish density. One reason for the large variation in fish density is likely that the probability and type of environmental impact varies according to reservoir characteristics and its role in the power production system. Traditionally, environmental management of Norwegian reservoirs has focused mainly on the potential effect of maximum regulation amplitude, meaning the difference between the HRWL and LRWL. This is probably based on the assumption that large amplitude is more negative for fish than a small amplitude. However, when looking at Figure 13, it is clear that this is a too simplistic view. If we want to understand how water level fluctuations affect fish populations in reservoirs, we must consider the full operational regime and variation over time, including amplitude, timing, frequency, and rate of change of the water level (Hirsch *et al*. 2017, Eloranta *et al*. 2018). This is in accordance with the hydrological methods already described in the handbook for environmental design in regulated rivers. However, the methods are not yet developed for such comprehensive analysis of water level fluctuations in regulated lakes.

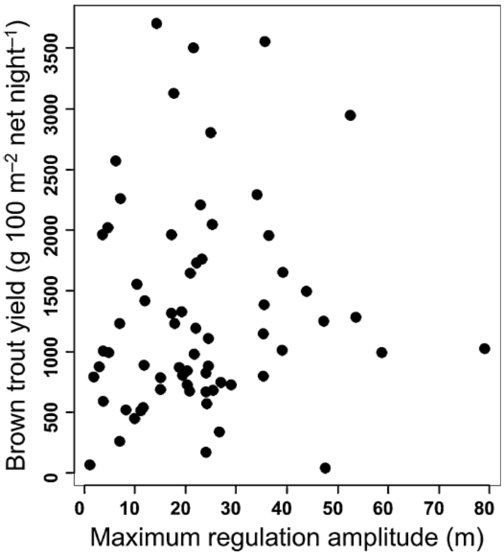

Figure 13. Biomass of brown trout of 67 Norwegian hydropower reservoirs. No other fish species are present in these reservoirs and they are all located in comparable climatic zones. Figure from Hirsch et al. 2017.

In a recent study of brown trout populations in approximately 100 Norwegian reservoirs, several potential hydrological measures were explored (Eloranta *et al*. 2018). The study showed that increased frequency of water level regulations (i.e. more often sudden rises or drops in water levels) leads to increased trout population densities, but decreased condition of brown trout individuals (i.e. reduced weight - length relationship). The positive effect of increased frequency of water level regulations on brown trout density was unexpected[7], and to better understand the mechanisms behind this finding, more research is needed, particularly on identifying hydrological parameters that can describe the relevant short- and long-term ecological impacts.

Lake morphometry (i.e., size, depth profile and shoreline development) determine several fundamental properties of the ecosystem, including the availability, productivity and linkages between different habitats. These factors, in turn, shape the structure and function of lake food webs and the niche use of individuals and populations of fish. Recent results suggest that brown trout populations are least vulnerable to negative hydropower impacts in reservoirs that are relatively large and deep and host no other fish species (Eloranta *et al*. 2018). Such reservoir ecosystems likely provide sufficient habitat and food resources for brown trout, even if they must move away from the impaired shallow littoral zone and utilize the less affected food and habitat resources in open and deeper areas. In small or multi-species reservoirs, superior competitors may exclude brown trout from these alternative habitats. Understanding such dynamics between species interactions, reservoir characteristics and water level fluctuations is important in order to identify in what types of reservoirs and under which kinds of hydropower operations fish may be most vulnerable.

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[7] See the discussion in Eloranta et al. 2018 for possible explanations.

3.2 Diagnosis phase for hydropower reservoirs

Theoretically, one could probably use a similar approach for fish in reservoirs as in rivers. Access to spawning area and shelter are likely important bottlenecks for fish also in reservoirs. Similarly, hydrological variations and temperature may influence growth and habitat conditions for reservoir fishes, just like in rivers. Hence, many of the methods described in the handbook for environmental design are conceptually relevant for reservoirs, but they must be adapted to parameters relevant for lakes and resident fish populations. However, there has not been a tradition for mapping habitat conditions and hydrological patterns in Norwegian reservoirs. Traditionally, surveys of fish populations in Norwegian reservoirs have focused on population data, usually based on gill-net sampling of adult fish. In addition to estimation of total population biomass, the fish catches are usually analysed for individual fish size, age and growth, which can be used for classical life-history parameters like size and age at sexual maturation and year class strength. This kind of fish individual and population data are suitable and highly needed for correct diagnosis in reservoirs.

In the salmon handbook, the structure of the diagnosis phase is built on identifying habitat-related and hydrological bottlenecks affecting fish production, while population data are used mostly as support. This is because one is looking for bottlenecks limiting the production of juvenile fish, i.e. what regulates the number of salmon smolts migrating from the river to the sea, and the number of juveniles in rivers is largely controlled by habitat availability and hydrology. Given that reservoir fishes live their adult life in the lake and it is more feasible to collect adults than juvenile fish in lakes, it is reasonable to use population data collected from catches of adult individuals when setting the diagnosis. Therefore, we suggest that a handbook for environmental design for reservoirs should rely more on population data in the diagnosis phase than what is often done in the salmon rivers. However, also in reservoirs the population data must be supported by data on habitat and hydrology.

An aspect which is not included in the salmon handbook, but which is of high importance for a future handbook for reservoirs, is collecting information on lake productivity, such as nutrient levels and water quality. Prey availability is more important in lakes, since resident fishes complete their entire life cycle in the lake, unlike the anadromous salmon, who migrate to the sea where food is more abundant to grow large. If decreased nutrient level or decreased water quality has significantly altered the food web in the reservoir, this will influence fish populations. Hence, when looking for bottlenecks in reservoirs, an additional population-regulating factor to habitat-related and hydrological conditions may be food limitation.

Hence, we suggest that the diagnosis phase for environmental design for reservoirs should consist of two parts: one based on data on fish populations and their main prey, and the other on hydrological and habitat data. In addition, the hydropower system must be described to understand the regulation effects. These three aspects are described in more detail in chapter 3.4– 3.6.

3.3 Main areas to investigate in reservoirs

All main lake habitats, i.e. littoral, pelagic and profundal areas, see Figure 14, should be investigated when looking for the diagnosis, but the degree of details needed is not the same in all areas. For example, while survey fishing (e.g. gill nets) is recommended in all habitats, mapping of bottom substrate is not as important in the profundal as in the littoral zone. If stream spawning fishes are present, the inlet and outlet streams should also be mapped at a fairly detailed level. In the inlet and outlet streams, the methods developed for salmon rivers can likely be used directly, while a new classification is needed for lake habitats. Although a classification system for how to split lake areas into relevant mapping areas is not yet created, there are available tools that can be used to collect relevant information. Hence, it is feasible to create a classification of ecologically relevant lake areas for a future environmental design handbook for reservoirs.

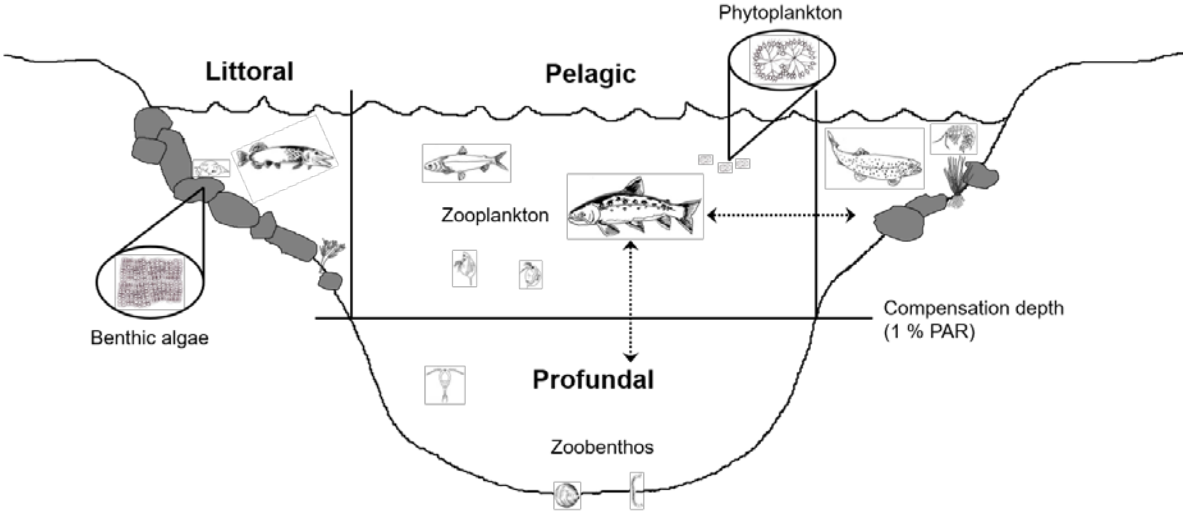

Figure 14. Illustration of main habitats and ecosystem components in lakes. Figure from Eloranta 2013.

For areas in the littoral zone, it is useful to use aerial photos from sources like www.norgeibilder.no to identify which parts of the littoral zone seem more or less exposed. While some reservoirs are uniformly shaped, others have many bays and a higher shoreline complexity. Thus, some parts of the littoral zone may be more exposed to wind, ice scouring and erosion than others. Further, one should compare the lake area at HRWL and LRWL to identify all areas exposed to drying. In some cases, aerial photos may be available from situations close to HRWL and LRWL. Otherwise, this can be mapped with new drone photos at relevant times or be modelled from a hydrological model if bathymetric maps are available. For the littoral area below LRWL, an underwater drone can be used to obtain visual information on substrate and submerged vegetation along the shoreline. Based on all this information, one can divide the littoral zone into parts that are expected to have more uniform habitat and hydrological conditions, which thereafter can be mapped in more detail.

For the open water areas, temperature and light conditions can be used to separate different habitat zones. The profundal zone is separated from the pelagic zone based on how deep light (i.e., 1% of surface solar radiation) can penetrate, as illustrated with the compensation depth in Figure 14. In addition to light penetration, temperature is important to classify reservoir habitats since many Norwegian lakes become thermally stratified into three identifiable layers during summer (Figure 15). The epilimnion is the upper, warm and well-mixed layer. Below this is the metalimnion or thermocline, a layer of water in which the temperature drops rapidly with increasing depth. Below the thermocline is a zone of cold water called the hypolimnion. Because of the change in density, the thermocline functions as a barrier that limits mixing of water between epilimnion and hypolimnion during the summer stratification period. Hence, epilimnion and hypolimnion can be seen as two distinct habitats and many organisms do not cross the thermocline.

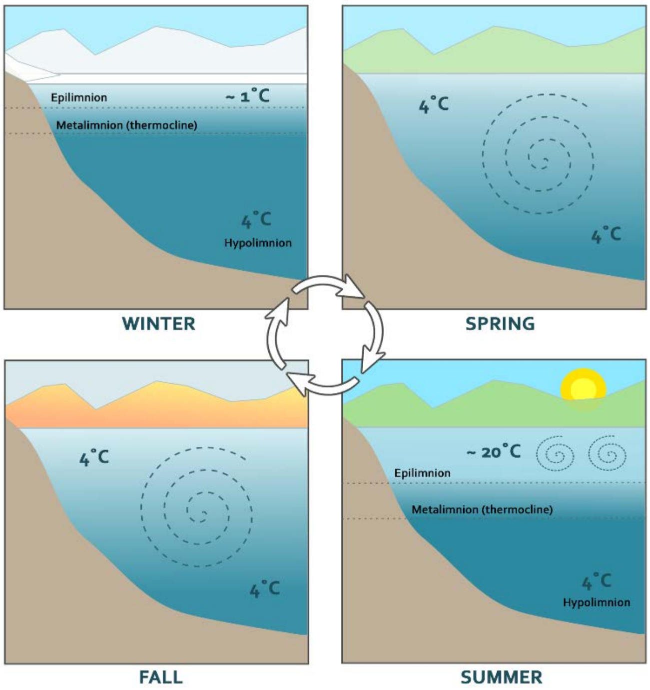

Figure 15. Pattern of temperature stratification and mixing in Norwegian lakes. Figure by S. Skoglund, NINA.

Temperature stratification is not constant but varies with seasons and between years. Generally, the water temperature layers mix during spring and autumn, and form again during summer and winter, as seen from Figure 16. During winter, the warmest water of 4° C is at the bottom of the lake, while colder water stays close to the surface or ice cover. To collect necessary data on habitat conditions in open water, temperature measurements at different depths throughout the water column should be performed during the year. The best way to achieve such data is to place sets of temperature loggers in the reservoir that can collect continuous data over several years. Such information is crucial to create a proper evaluation of regulation impacts and hydrological bottlenecks, as data from loggers are also needed to perform hydrological modelling of the lake (see more about this in chapters 3.5 and 3.6)

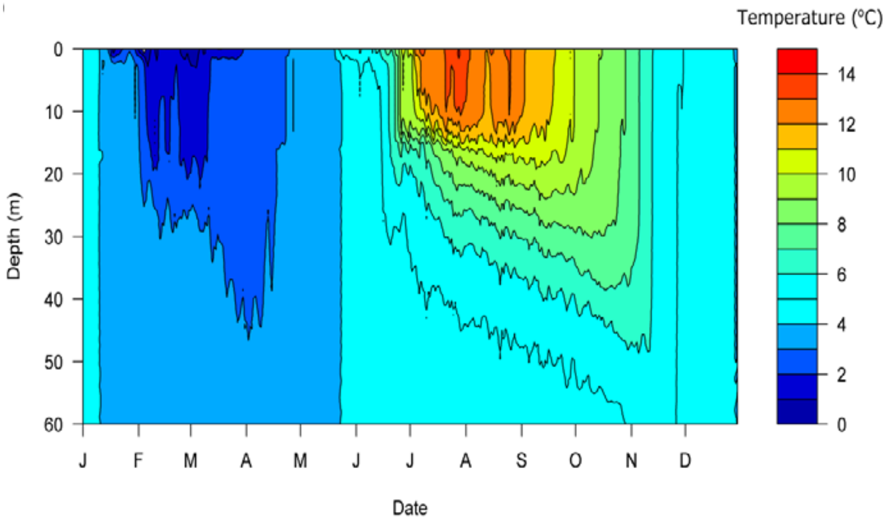

Figure 16. An example of isothermal variations of a Norwegian reservoir. The figure shows data from temperature loggers in the upper 60 metres of Suldalsvatnet (regulation amplitude 1.5 m) in 2001. Figure created by R. Hedger, NINA.

Another aspect to consider when defining relevant areas to survey when looking for the diagnosis is that many reservoirs may consist of several basins that are partially disconnected from each other. Different basins with different depth profiles are often found when damming has resulted in formation of one large reservoir made from several smaller lakes, as illustrated in Figure 17. In some reservoirs, the different basins can be separated by islands or necks of dry land at LRWL and be connected into one large lake at HRWL. Long, fjord-like reservoirs may also have longitudinal changes in biotic and abiotic factors from one end to the other, and thus these areas should be mapped separately. Large fjord-like reservoirs may also experience substantial currents and alterations of the thermocline caused by varying wind exposure.

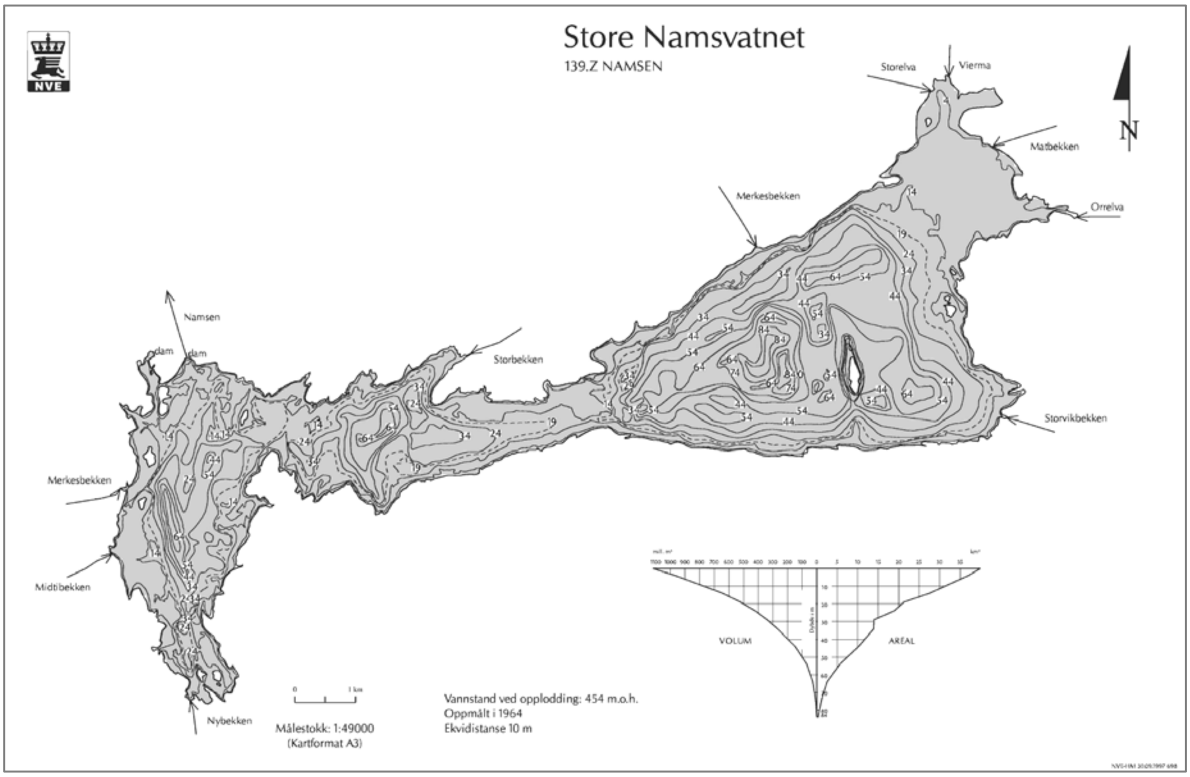

Figure 17. The reservoir Store Namsvatn was created after dam construction in 1959 from four smaller lakes (Lillevatnet, Sørvatnet, Midtivatnet and Store Namsvatn) separated with narrow necks of water. The regulation amplitude is 14 m.

3.4 Fish populations and their main prey

As brown trout is common in Norwegian lakes and reservoirs and among the best-studied fish species, there is good knowledge on how to evaluate the status of trout populations. Therefore, the design phase of a future handbook for environmental design in reservoirs could build on already existing methodology for evaluation of brown trout population status. The fish surveys conducted in Norwegian reservoirs are generally based on gill net catches for selected species (usually brown trout and Arctic charr), mostly in nearshore (littoral) or shallow open water (pelagic) areas and performed late in the growing season (August-October). The catches are usually analysed for life-history parameters based on information about individual fish size, growth, age and sexual maturation. Further, catch per unit of effort (CPUE) can be calculated and used as a proxy for total biomass of catchable fish. In reservoirs with brown trout, electrofishing for juvenile fish in inlet or outlet streams is often performed, since these are important recruitment areas for stream-spawning populations. The extent of within-lake spawning of brown trout is largely unknown, but may be frequently occurring (Arostegui and Quinn 2019). Even if multi-mesh gill nets are used, the smaller fish sizes are underrepresented in catches. However, based on back-calculation of growth from scales or otoliths, one can retrieve information also about young fish. See for example Lie *et al*. (2018) and Kanstad-Hansen (2012) for description of such traditional fish surveys in Norwegian reservoirs.

As written in chapter 3.2, the methods from these traditional gill net surveys are well suited to use for the diagnosis phase of environmental design in reservoirs. One must consider the whole fish life cycle to find the right diagnosis. Different fish species, age classes and size groups have different environmental needs and bottlenecks can occur either during spawning or at the larval, juvenile or adult stage. This necessary information of species composition, density, growth and year class strength can be retrieved from gill net surveys. Indications of hydropower induced bottlenecks can be

i) unexpected dominance between fish species
ii) lack of certain year classes
iii) reduced growth
iv) early sexual maturation
v) unexpected distribution of fish among littoral and pelagic areas

If any of these signs are seen from the gill net surveys, there is a need to do further sampling of physical and chemical properties. Since there is large natural variation in recruitment and population sizes among lake fish populations, particularly brown trout, the above-mentioned signs may not always be results of hydropower impact. Hence, hydrological analyses and habitat mapping is needed to fully set the diagnosis and to confirm that potential design solutions will have the desired effect (see chapter 3.5).

If trout spawns in streams, any limitation in recruitment areas in such inlet and outlet streams can be a population bottleneck, even in unregulated lakes. If all trout spawning is assumed to occur in streams, one can use the so-called recruitment ratio (*oppvekstratio* or OR) to identify how much trout to expect in the lake (Anonymous 2018). This is the ratio between the area of the stream spawning habitats and the total lake area. Thus, before one conclude that the spawning has been reduced due to hydropower, one should consider if the trout population in question may have a naturally low recruitment. It is worth to note, however, that one of the benefits of the environmental design concept is the recognition that hydropower regulation also gives the possibility to create environmental properties particularly favourable for fish, potentially more favourable than under natural conditions. Some of the environmental design projects in salmon rivers aim to result in win-win situations, with more salmon and more hydropower production simultaneously[8]. However, it is often more realistic to achieve win-neutral situations, meaning that the fish population will benefit without any substantial loss in power production. Conceptually, one could imagine similar possibilities for environmental design in reservoirs, where design solutions could improve spawning conditions for naturally thin brown trout populations, and thereby increase the harvestable surplus, without having a loss in hydropower production.

A useful characterisation system for evaluation of brown trout populations which could be implemented in a handbook for environmental design for reservoirs is the system developed by Ugedal *et al*. (2005) (Figure 18). This system is based on gill net catches. Mean size of sexually mature females (or other similar growth measures) is used as an indicator of growth conditions, and divided into three classes: small fish (< 25 cm), medium-sized fish (25–35 cm) and large fish (> 35 cm). This is used in combination with an indicator of population density, measured as catch per unit effort, and the three classes: low density (< 5 fish per 100 m^2 gill net per night), medium density (5–15 fish per 100 m^2 gill net per night) and high density (> 15 fish per 100 m^2 gill net per night). This gives nine different classes of brown trout population status, as seen in Figure 18. For the development of a handbook for environmental design for reservoirs, such an approach, perhaps with some modifications, is useful since it can indicate if the population size and the fish growth is as expected or not, and thus be an important part of a diagnosis.

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[8] https://www.cedren.no/Nyheter/Article/ArticleId/4221/Gar-det-an-a-produsere-lonnsom-vannkraft-og-samtidig-ta-hensyn-til-naturen

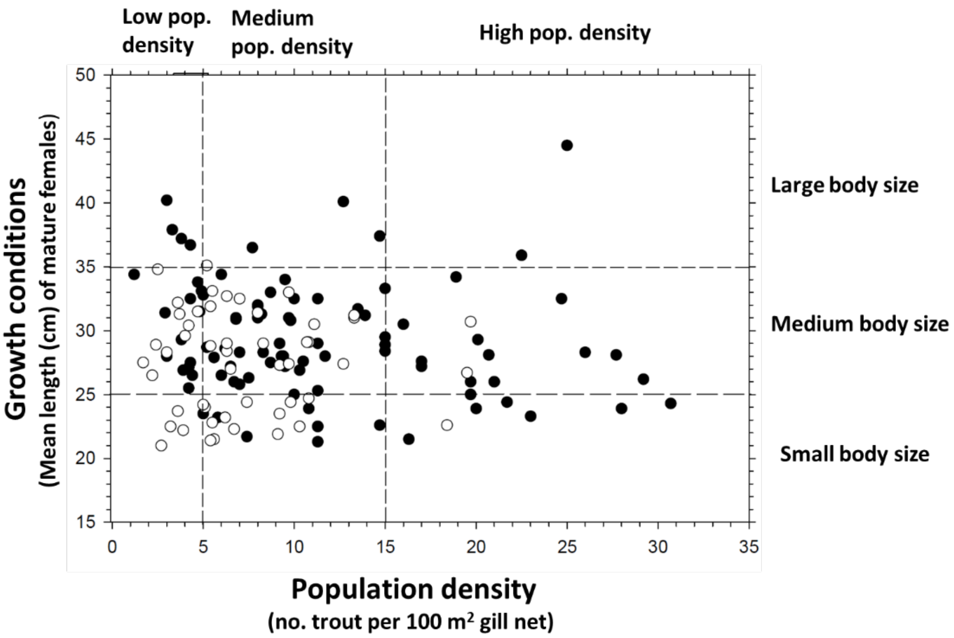

Figure 18. Nine combinations of population status of brown trout, based on growth conditions (three classes) and population status (three classes) Black dots show lakes with brown trout as the only fish species, while white dots show brown trout populations coexisting with other fish species. Figure modified from Ugedal et al. 2005.

Water level fluctuations in reservoirs cause desiccation, freezing and erosion of the littoral zone, which lead to physical and biological deterioration of the shallow bottom areas of the lake. These areas are usually the biologically most productive areas in natural lakes (Strayer and Findlay 2010). Hence, when they are heavily impacted by regulation and important plants and bottom-dwelling organisms disappear from the littoral zone, the whole food web is affected and the overall lake productivity decreases. Usually the traditional fish surveys in Norwegian reservoirs consist of diet analyses of the fish, based on stomach contents to identify main prey items. Stomach contents analysis reflects the recent diet of fish and it can reveal the occurrence of some important fish prey items (e.g. *L. arcticus*, *G. lacustris*, *M. relicta*) in the ecosystem. However, temporal variations in diet is often lacking, unless repeated sampling has been performed at different times of the year. In recent years, stable isotope analysis has been applied in a few cases, improving the understanding of trophic interactions throughout the growing season. Stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotopes reflect the long-term assimilated diet of fish and the overall food-web structure in the ecosystem. Most importantly, stables isotopes can be used to estimate reliance of fish on littoral food resources and food-chain length in the ecosystem, which can both be heavily affected by water level regulation in hydropower reservoirs (e.g. Eloranta *et al*. 2016 and references therein).

Sampling of benthic invertebrates can be of interest to evaluate if the different habitats are still able to fulfil their ecosystem function under the variations in water levels. If key species are missing, this can indicate bottlenecks for fish, if their prey availability is strongly reduced. However, sampling of benthic invertebrates in sufficient amounts and in a representative manner can be resource demanding and thereby costly. Here, promising tools are under development that may be highly important for future environmental design projects (in both rivers and reservoirs), namely the use of e-DNA to characterize biodiversity and identify key species[9]. Further, species composition and body-size of key zooplankton groups (e.g. daphnids and bosminids) in the pelagic area can give important information about the predation pressure by fish in the pelagic zone. Such information is particularly relevant in reservoirs with planktivorous species like Arctic charr and whitefish.

As seen from the text above, there are already several sampling technics and evaluation systems available that can be used in a future handbook of environmental design in reservoirs. However, there is a need to implement

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[9] See e.g. this ongoing project https://www.ntnu.edu/hydrocen/4.3-multiple-interests-under-future-flexible-hydropower-operation

standardized surveys to ensure that sufficient data is collected in all reservoir monitoring. If standardized methodology is used, this also opens up for the possibility to compare data between surveys, which would enable us to understand more of the general mechanisms for how reservoir fishes are impacted by different hydropower operations, rather than simply study each reservoir separately. To facilitate a future protocol for standardized surveys, we have summarized the main methods to study fish populations and their main prey items in Table 2. All these methods are well-established and applicable for environmental design in hydropower reservoirs. However, it is still necessary to combine the biological information with other type of data, such as habitat mapping, to identify the bottlenecks and to find suitable design solutions

Table 2. Tools to map fish populations and main prey

Sampling	Necessary information	Purpose for diagnosis	Scope
Survey fishing	Species, sex, length, weight, age, maturity, density and biomass in different habitats	Necessary to study community composition, density, growth and age distribution of dominant species to evaluate fish population status. Signs of negative regulation impacts that should be studied more (in terms of physical and chemical conditions) include unexpected dominance relationships between species, lacking year classes, reduced growth, early maturation and unexpected ratio of catches in the shallow and open-water areas.	Already part of ordinary fish surveys. Basis for evaluation of ecological status under *vannforskriften*. Nordic survey gillnets is the standard method, but ordinary gillnets with varying mesh sizes can be expedient.
Fish stomach samples	Stomach fullness, relative proportion of different prey taxa, presence of particularly important prey taxa (e.g. *Gammarus* sp. or *Lepidurus* sp.).	Stomach contents analysis reveals food availability, fish position in the food web, use of shallow- and deep-water food resources, and existence of important prey taxa in the reservoir.	It is not necessary to identify species and count every prey item in the stomach sample, but one should at least estimate the relative (volumetric) proportions of different prey taxa. Could be useful to develop a common, standardized sampling protocol.
Stable isotope analyses	Stable carbon and nitrogen isotope analyses of samples collected from benthic algae and invertebrates in shallow bottom areas, from pelagic zooplankton and from fish dorsal muscle tissue.	Provides valuable information about the ecosystem structure and importance of shallow- and deep-water areas for the lake food web (following e.g. potential negative hydropower impacts on the littoral zone). Reflects fish diet over a longer time period than the	Sampling of stable isotope data in late summer/autumn becomes cost-efficient because traditional early-season sampling can be excluded. Sampling of fish muscle tissue is very easy, but sampling of other

	Sampling of deep-water (profundal) benthic invertebrates is desirable whenever possible.	traditional ”snapshot” stomach contents analysis.	organisms may be more demanding. The samples can be sent and analysed (relatively cheaply) in a stable isotope laboratory. It could be useful to develop a standard protocol for sample collection and preparation.
Benthic invertebrate samples	Invertebrate community composition (species/functional groups) in shallow and deep areas. If possible, quantitative data of species' abundance would be desirable.	Benthic invertebrate community reveals if different habitats still function despite hydropower-regulation. Absence of specific taxa may indicate negative regulation impacts and reduced food availability for fish.	It can be difficult and time demanding to find enough material in some reservoirs. New methods with use of eDNA looks promising.
Zooplankton samples in pelagic areas	Species composition and size distribution of key groups	Give information about the predation pressure by fish in the pelagic zone and thus potentially reduced food availability.	Particularly relevant in reservoirs with planktivorous species like Arctic charr and whitefish.

3.5 Hydrology, water chemistry and habitat mapping

As written in the previous section, the collected biological information must be combined with data on environmental properties to fully identify the bottlenecks and to find suitable design solutions. Although the gill net data and food-web analyses can indicate whether the fish population is healthy or if there seems to be bottlenecks, they may not give necessary details on when the bottlenecks take place and where to implement suitable measures. For example, if the population data indicate recruitment failure due to missing year-classes, it cannot be told from the fish population data alone if the bottleneck occurs during spawning (e.g. lack of access to spawning habitat), or at the juvenile stage (e.g. lack of shelter and food for young fish). Further, if the fish growth is lower than expected, further investigation is needed to find out whether low growth is due lack of food alone or if other process like changes in temperature and ice-cover or increased competition for shelter is also involved in reduced growth. Hence, hydrological analyses and habitat mapping is needed to fully set the diagnosis and to confirm that potential design solutions will have the desired effect.

In contrast to data on fish populations and their main prey, habitat mapping and hydrological analyses have been lacking in most reservoir surveys. In many cases, appropriate habitat mapping is done in the adjacent spawning streams, but any form of habitat mapping is rarely done within the reservoir itself, i.e. in lake habitats. Hence, there are knowledge gaps in our understanding of how hydropower operations regulate reservoir fish populations. However, even if we do not have a developed diagnosis system yet, there are many available tools that can be used for data collections of both abiotic and biotic properties of lake habitats and hydrology. In addition, a fast method development will make future data collection easier and more cost-efficient e.g. due to increased use of remote sensing, automatic monitoring devices and drone photos. We have summarized the tools we suggest to use in Table 2 and we want to emphasise that we consider most of these methods to be easy to use and not too expensive. We strongly recommend that the tools listed in the table are used in combination with the tools in Table 2 and together become implemented as part of standard protocols for data collection in reservoirs.

To evaluate the effect of hydropower on fish population, information on how much of the habitats that are modified or missing is needed. Therefore, knowledge of how large proportion of the total lake volume and extent of the littoral zone that get impacted by water level regulations is important. However, as far as we know, most reservoirs lack proper bathymetric maps and thus basic morphological features like maximum and mean depth or lake volume are undescribed. According to Bakken *et al*. (2018), maximum depth is only available for 10 % of the reservoirs in the database of NVE. Without this knowledge it is difficult to evaluate the extent of hydropower impact, therefore bathymetric maps should be created for all hydropower reservoirs in Norway. This can be done with multi-beam echo-sounding. Depth maps are also important to evaluate if different basins of the reservoir may be separated from each other at LRWL.

Fundamental limnological features, like depth and development of the thermocline, time of spring and autumn mixing and duration of ice-cover is important information to understand available habitats and to evaluate the growth conditions for fish and main prey. This can be easily mapped by using temperature loggers at different depths over several seasons and years. Hydropower operations often modify these limnological factors and can thus influence both habitat availability and growth conditions for fish. For example, the length of the growth season as well as the duration of the ice-covered period, influence the biological productivity and thereby the growth conditions for fish. By affecting ice-cover dynamics, hydropower operations may influence both chemical and physical conditions in the reservoir, and thereby the growth of fish.

To evaluate how hydropower operations may influence the extent of lake spawning habitat for adult fish, shelter for juvenile fish and habitat availability for important prey species, it is useful to map bottom substrate quality (e.g. stones, sand, silt), benthic algae and submerged vegetation, particularly in the littoral zone, but also partly in deeper areas. Such mapping may also reveal whether the geological conditions within the regulation zone (between HRWL and LRWL) are vulnerable to erosion and increased turbidity. Techniques like mini-ROV to film below water in combination with multi-beam echo-sounding can be useful here. If such methods are tested in some reservoirs, one could aim to create habitat classification tools for a future handbook, similar to those included in the salmon handbook.

Another important benefit of including such habitat mapping in standard sampling protocols is that more information on habitat details below LRWL can fill some fundamental gaps in our knowledge. Since this type of mapping have rarely been done, several mechanisms for how habitat and hydrological features are limiting fish populations are poorly understood. For example, we do not know properly which habitat characteristics that best describe spawning areas for lake spawning fishes like Arctic charr or whitefish, although it seems clear that different populations use different types of spawning habitat (Næsje *et al*. 2004, Miller *et al*. 2015, Arostegui and Quinn 2019). Another example of unknown mechanisms is the role of available shelter in regulating the population. While we know that rocks and plants in the littoral are important shelter for small fish that need to avoid predation (Strayer and Findlay 2010), it is not clear how density-dependent competition for shelter and littoral food may regulate fish production in Norwegian lakes and how this may vary between species. Such information is not only needed in hydropower reservoirs, but would also be needed for evaluation of all lakes according to *vannforskriften*. We also lack knowledge on individual fish movement between different habitats. Within a lake, fish individuals may specialize their feeding and habitat use in separate ecological niches, e.g. by predominantly using either littoral, pelagic or profundal areas (e.g. Harrod *et al*. 2010). Such niche specializations may influence their sensitivity to hydropower-induced water level and temperature fluctuations. It is likely that water level fluctuations due to hydropower regulation may influence fish activity, for example their need to move to other areas to find food, which again will influence their bioenergetics and growth.

To understand the growth potential of the fish population, information on the biological productivity and turbidity in the reservoir is important. Water samples tested for the main biogeochemical properties (e.g. totP, N, pH, DOM, turbidity) is easy to perform. Further, measurements of Secchi-depth can tell how deep the primary production occur (see Figure 14). This is important information to evaluate how large proportion of the productive lake area that is impacted by water level fluctuations. In addition to drying of the littoral, water level fluctuations in reservoir frequently cause flooding of originally dry land areas. This typically increases physical erosion of the riparian zone and results in internal and external loading of dissolved nutrients, carbon and pollutants, subsequently decreasing the reservoir water quality. This effect will vary over time. In the early years after the reservoir is created, the potential increase in availability of autochthonous and allochthonous resources may lead to increased biological production. However, after a while, a trophic depression (or oligotrophication) may occur when organic matter and nutrients are exhausted or rendered unavailable by sedimentation. Water level regulations can also affect the light attenuation within the water column because of increased resuspension of fine particles (e.g. clay, silt or humus). Many reservoirs in Norway have very turbid water due to high resuspension of silt from the sediment to the water column, which is still evident decades after the onset of hydropower operations (Eloranta *et al*. 2016). The resulting decrease in water clarity can reduce both primary production and secondary production in the reservoir, due to light limitation. In addition to water chemistry and Secchi-depth information about the land cover in the catchment area (e.g. proportion of forest, bog, mountains) can also be useful to understand the biological productivity of the reservoir. Information about human activity in the catchment areas can also give information about other impact than hydropower. Such information is already in use when classifying lakes and reservoirs according to *vannforskriften*.

Table 3. Tools to map physical and chemical habitat conditions in reservoirs

Sample type	Necessary information	Purpose for diagnosis	Scope
Depth measurements e.g. with echosounder	Bathymetric (depth) map. The accuracy (resolution) should be highest in the shore areas (2.5 x Secchi depth or uppermost 30 m). Here a side-scan echosounder can be very useful.	Regulation impacts are difficult to evaluate without knowing how much of the total lake volume and shore areas are affected due to water level regulation. Shore areas are the most important habitats in lakes, but also the most sensitive habitats in hydropower reservoirs. Depth map is also important for evaluation of connectivity between separate lake basins during low water level periods.	Can be performed independently of biological studies. Needs to be conducted only once in each reservoir.
Temperature measurements at different depths (e.g. with loggers)	Water temperature fluctuations at different depths throughout the year. It is important to measure temperatures at narrow intervals (e.g. every meter) in uppermost water column, whereas fewer sampling points are enough in deeper areas.	Information about temperature zones, thermocline depth and timing of spring- and autumn-mixing are necessary for understanding habitat availability and growth conditions for fish and their prey organisms.	The minimum data to collect is water temperature profile throughout a summer period, i.e. from spring- to autumn-mixing. In the best case, temperature recordings should be done in several years to observe potential annual variations, especially if the water level regulation pattern differs between years.
Survey of ice-cover period	Timing of ice formation and melting.	Length of growing season and length of ice-covered period affects biological productivity and growth conditions for fish. Regulation may affect ice stability and thereby reservoir's chemical	In some reservoirs, ice can be inspected visually, whereas in other places a monitoring camera may be useful.

		and physical conditions and fish growth.	
Survey of bottom substrate (underwater viewer, camera, scuba diving, remote operational vehicle, multi-beam echosounder etc.)	Amount of areas covered by sand, gravel, small and large stones and barren bedrock. Amount of vegetated areas. Amount of areas covered by other organic matter (e.g. woody debris and dead plants).	It is difficult to estimate potential negative impacts of regulation without knowing how large suitable spawning and shelter habitats for fish are affected by regulation. Bottom surveys also enable estimation of the shore vulnerability to erosion, increased turbidity and clogging of important fish habitats.	Quantitative surveys are not necessary, but a qualitative evaluation of different bottom areas should always be reported. In large reservoirs, thorough bottom surveys are impossible and thus a representative shore survey area should be selected. Aerial photographs (norgeibilder.no) can be helpful in planning.
Survey of potential spawning streams around the reservoir	Amount of stream spawning habitats. Evaluation of connectivity between the reservoir and streams at different water levels, and existence of potential migration barriers.	It is difficult to evaluate potential negative impacts of regulation without knowing how large proportions of suitable spawning habitats are affected by regulation. *Oppvekstratio* (share of spawning/nursing habitats in total lake area) is an important parameter for evaluation of trout population status (according to *vannforskriften*).	Electrofishing is the best method to detect spawning areas in streams, but visual inspection of habitat quality can substitute electro fishing. Deployment of camera to check if there is sufficient water to ensure fish migrations at different times may be relevant.
Survey of potential spawning areas within the reservoir	Location of spawning areas for lake-spawning fish.	It is difficult to evaluate potential negative impacts of regulation without knowing how large proportions of suitable spawning habitats are affected by regulation.	It can be time-consuming to find spawning areas in lakes with today's methodology. Local knowledge can be of great help.
Water transparency measured with Secchi disk	Water transparency	Minimum information about the lake's productivity or turbidity is important to understand the nutritional base of fish. Water transparency indicates how deep primary production is possible. Necessary to determine how much of the lake's productive zone is affected by water level regulation	Very easy and quick to conduct simultaneously with the survey fishing. Repeated sampling at different times of the year provide better information, but one sample is also useful. Aerial photos from different times (norgeibilder.no) can be used as support, because water colour is often visible.

Simple water sample	Total phosphorus and nitrogen, pH, DOM, turbidity, water colour, ANC, chlorophyll-a.	Information about the lake's productivity and turbidity is important to understand the nutritional base of fish.	Very easy and quick to conduct simultaneously with the survey fishing. Cheap laboratory analyses. Repeated sampling at different times of the year provide better information, but one sample is also useful.
Survey of catchment area	Land use, any sources of possible pollution, possible runoff from glacier	Information about the catchment characteristics (forest, marsh and mountain areas etc.) indicates potential biological productivity in the reservoir. Information about other human activities reveals potential other impacts on the ecosystem than regulation. Together, this provides information about the nutritional base of fish and the reservoir's expected reference condition. Included as a basis for fish indices when classifying ecological condition (*vannforskriften*).	Basic information can easily be obtained from maps or aerial photos (norgeibilder.no), and from nevina.nve.no, where distribution of area types in the catchment is calculated. Visual inspection of field work areas may supplement.

3.6 Power generation and reservoirs

In environmental design, it is essential to assemble all relevant information about the hydropower system in order to have the necessary basis to set the diagnosis and evaluate potential measures (Forseth and Harby 2013). Here, input from the power plant operator is crucial to get information about the whole watershed, such as volume and water level regulations in all reservoirs, penstocks, tunnels, power plants (power output and capacity), where the water is drawn out of the reservoir, and information on the power plant intake and outlet. The focus in a handbook for reservoirs should naturally be on how the power system influences the reservoir in question.

The difference between HRLW and LRLW is not enough to evaluate the effects of the operational regime, the full water level fluctuation curve over time is needed. Ideally the measurements should be daily, but weekly data can be sufficient. Time-series of measured water levels in hydropower reservoirs are available in the NVE database Hydra II[10]. However, even if the data from the power plant operator can be used in several models (e.g. MyLake or CE-QUAL2, see Vaskinn 2010) that can produce numerous hydrodynamic variables, it is not clear what type of hydrological variations that are of relevance for a handbook for environmental design. Studies have shown that changes in ice-cover can modify interactions between fish species (e.g. Helland *et al*. 2011), and it is well known that temperature is an important driver for fish growth. However, it is unclear how hydropower-induced changes in ice-cover, water temperature and mixing regulate fish populations. While the salmon handbook has a set of defined hydrological parameters known to be important for salmon (e.g. variation in water-covered area as a function of flow, changes in the lowest weekly average flow, changes in the frequency and magnitude of flooding events), there is not yet any consensus on which hydrological metrics to use when looking at ecological effects of hydropower in lakes.

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[10] https://www.nve.no/hydrologi/hydrologiske-data/historiske-data/data-i-hydra-ii-databasen/

A recent study tested the effect of water level regulation on brown trout populations in ca. 100 Norwegian hydropower reservoirs. For the study, a set of regulation metrics were calculated, describing the magnitude, frequency and duration of water level regulations: i) maximum regulation amplitude, ii) relative proportion of weeks with a sudden rise or drop in water level and iii) the relative proportion of weeks with exceptionally low water levels (Eloranta *et al*. 2018). Here, the conclusion was that the regulation impacts often depended on the reservoir natural characteristics, such as morphometry and fish community composition, but high regulation frequency seemed to induce development of dense populations of poor-condition trout (Eloranta *et al*. 2018). More studies exploring the mechanistic links between ecological response and hydrological metrics that capture variation in space and time are needed. However, although a full classification system has not yet been developed, we can already now use core information like extent of dried littoral areas, timing of critical low water periods and very rapid water level fluctuations. This information is highly useful when interpreting the patterns seen in the collected fish population data and their main prey.

In addition to the hydrodynamic pattern of water level fluctuations in the reservoir, similar information as described in the salmon handbook is relevant also for reservoirs, such as information on typical operational strategies, any restrictions in addition to HRWL and LRLW, as well as dams or other constructions linked to the plant operation. Information on fishways or other devices installed as environmental measures in the reservoir itself or in inlet and outlet streams must also be mapped. Further, an important step towards identifying design solutions is to simulate alternative operational strategies, based on data on runoff, reservoir capacity, waterways and energy prices. This is important to understand the costs linked to various potential restrictions that can be suggested to meet environmental requirements. However, present day power production models usually only consider the water volume available for power production (i.e. the volume between HRWL and LRWL) and do not consider the effects on the total lake volume. Therefore, to perform environmental design in reservoirs, such power production models must be used in combination with hydrodynamic models to simulate how different operational strategies e.g. influence water mixing and temperature within the reservoir. An example of how the combination of power price simulations and hydrodynamic modelling of a given reservoir can be used to evaluate environmental effects in reservoirs is shown in the HydroBalance roadmap (Charmasson *et al*. 2018) and
Figure 19.

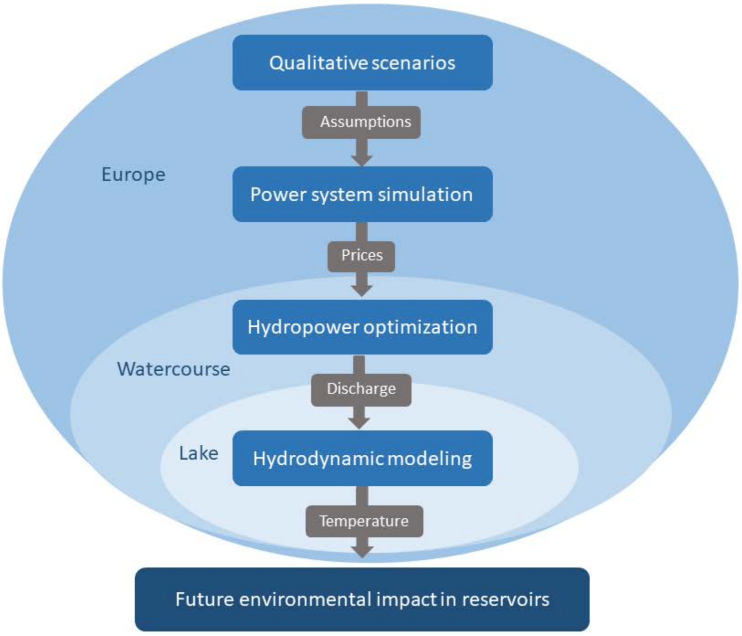

Figure 19. Description of methodological approach linking market simulations and future environmental impacts in reservoirs. Figure from Charmasson et al. 2018.

Another reason why hydrodynamic models should be used is that this is a good tool to evaluate the effect of present-day operational regime on the reservoir ecosystem. As explained above, there has been no tradition to survey how water level regulations influence the hydrological conditions in reservoirs, particularly not in the pelagic and profundal areas. Most focus has been given to the littoral zone and the regulation amplitude alone. Before a full handbook for environmental design of reservoirs can be written, more hydrodynamic modelling in reservoirs and particularly studies that link hydrodynamics to different operational regimes of the reservoir water level are needed. Here, it is important to emphasize that calibration of hydrodynamic models (e.g. CE-QUAL2) requires data on temperature profiles throughout the year, as well as proper bathymetric maps. Hence, temperature and depth data should be collected from all Norwegian reservoirs, as already noted in 3.5.

4 Identifying design solutions for hydropower reservoirs

4.1 Known mitigation measures in Norwegian reservoirs

After characterising a reservoir and making a diagnosis of potential bottlenecks limiting the fish population, the next step is to identify design solutions that can be expected to improve the environmental conditions in a cost-efficient way, i.e. without excessive socio-economic costs. According to the environmental design concept, it is important to combine all information on fish ecology, hydrology and the hydropower system, including alternative operational strategies of the hydropower production. Only when all these things are put together, one have the necessary basis to set the diagnosis and to identify suitable design solutions. To our knowledge, no one has so far performed a full environmental design project like this in a reservoir. However, there are a number of different mitigation measures that have been or are used today in Norwegian reservoirs, which may or may not be useful for a future handbook for environmental design for reservoirs. These mitigation measures are variable in terms of the financial, labour and time resources required, and their sustainability, general applicability and outcomes (Trussart *et al*. 2002, Glover *et al*. 2012). In this chapter, we will describe some of the most commonly applied mitigation measures for reservoir fish and discuss their pros and cons. We focus on measures implemented in Norway, but some examples from other countries are also included.

In 2006, the County Governors (*Fylkesmannen*) were given the authority to impose environmental surveys and measures in all regulated watersheds, apart from anadromous rivers that are under the authority of the Norwegian Environment Agency. Thus, the County Governors are responsible for environmental surveys of plants and animals in all hydropower reservoirs, as well as other environmental aspects relevant for recreation and outdoor life (Anonymous 2017). However, the rights of the County Governor to demand the power companies to perform surveys and implement measures must have been defined in the terms of the given power regulation (*konsesjonsvilkår*). In most cases, the terms are given in such a way that the County Governor have *the right* to impose environmental surveys, but they have *no obligations* to do so. In addition to the role in following up on environmental status of lakes and inland rivers regulated for hydropower, the County Governors are also responsible for coordinating the operational monitoring according to *vannforskriften*. Hence, it is the responsibility of the County Governors to collect data about the status of water resources and assess their environmental status, monitor and identify problems and act as an environmental advisor to other authorities involved in water management in Norway.

Since the County Governors are responsible for environmental measures in hydropower reservoirs, we have contacted all of them to obtain information about the type of measures that have been tested in Norway, including where and how often. In some cases, mitigation measures may have been initiated as a voluntary agreement between local stakeholders and the hydropower companies, without any demand from the County Governors, but still the County Governors are usually informed and/or involved. Thus, we assumed that the County Governors would have the necessary information on most relevant reservoir mitigation measures conducted in their region.

Each County Governor was first contacted by e-mail and asked to report every mitigation measure done in their county to enhance conditions for fish in hydropower reservoirs. The e-mail was sent on behalf of the project coordinators by the project's contact person in the Norwegian Environment Agency on 05.10.2018 (see appendix 1). Later, the County Governors were given a reporting template (see appendix 2) by e-mail on 12.11.2018. Additionally, all of them were contacted by phone to make sure we received as much data as possible. We asked particularly for mitigation measures targeting brown trout, but pointed out that we were also interested in mitigation measures targeting other species. We expected that most measures were targeting brown trout as this is the most common species in Norwegian lakes and reservoirs and a species preferred by local anglers and fishers. Thus, the findings in this chapter focus on mitigation measures targeting brown trout, except from a few examples of other species mentioned in section 4.3.4. The land-locked salmon “bleka” in lake Byglandsfjorden is considered as “brown trout” due to the species' similar ecology and habitat requirements.

We received response from all County Governors, but four of them had no measures to report (see Table 4). Data from Telemark are not included in the analyses due to late response. In total 37 reservoirs with measures were reported, but in some cases numerous measures targeting the same reservoir had been implemented.

Table 4. Number of reservoirs with reported mitigation measures from different county governors. The numbers in the column "Total number of reservoirs" are taken from NVE database[5]. All reservoirs noted with hydropower are included, including those used for multiple purposes in addition to their role in power production.

County	Number of reservoirs with reported measures	Total number of reservoirs
Agder	1	108
Vestfold and Telemark*	0	112
Oslo and Viken	5	106
Innlandet	17	110
Rogaland	0	128
Vestlandet	5	323
Møre og Romsdal	0	83
Trøndelag	5	125
Nordland	4	151
Troms and Finnmark	0	72
Total	**37**	**1318**

* Telemark responded in May 2019 and reported one case of mitigation measures in an inlet river, but this was too late to include the data in our analyses.

The 37 reservoirs with reported measures differed greatly in size, altitude, regulation amplitude and the number of fish species present. The average size of the reported lakes was 27 km^2 and ranged between 0.12–369 km^2 (Figure 20 a). The lakes also differed remarkably in altitudinal location, ranging between 119–1223 m a.s.l. and averaging 579 m a.s.l. (Figure 20 b). No mitigation measures were reported from reservoirs located between 464 – 661 m a.s.l. The reservoirs' regulation amplitudes range between 0 – 47.5 m with an average of 9.7 m (Figure 20 c). The zero value is from a previously regulated lake, where mitigation measures were done to compensate for earlier damage.

The number of fish species present in the reservoir ranged between 1 – 20 (Figure 20 d). Most of the reported reservoirs are trout dominated (57 %, n=21) while some are either charr dominated (n=3), trout and charr dominated (n=2), dominated by coregonids (n=6) or cyprinid or percid dominated (n=5) (Figure 21). It is not surprising that most reservoirs are trout dominated since we asked for examples for mitigation measures targeting brown trout. However, brown trout is a valued resource, but mitigation measures are also done in hydropower reservoirs with more complex fish communities.

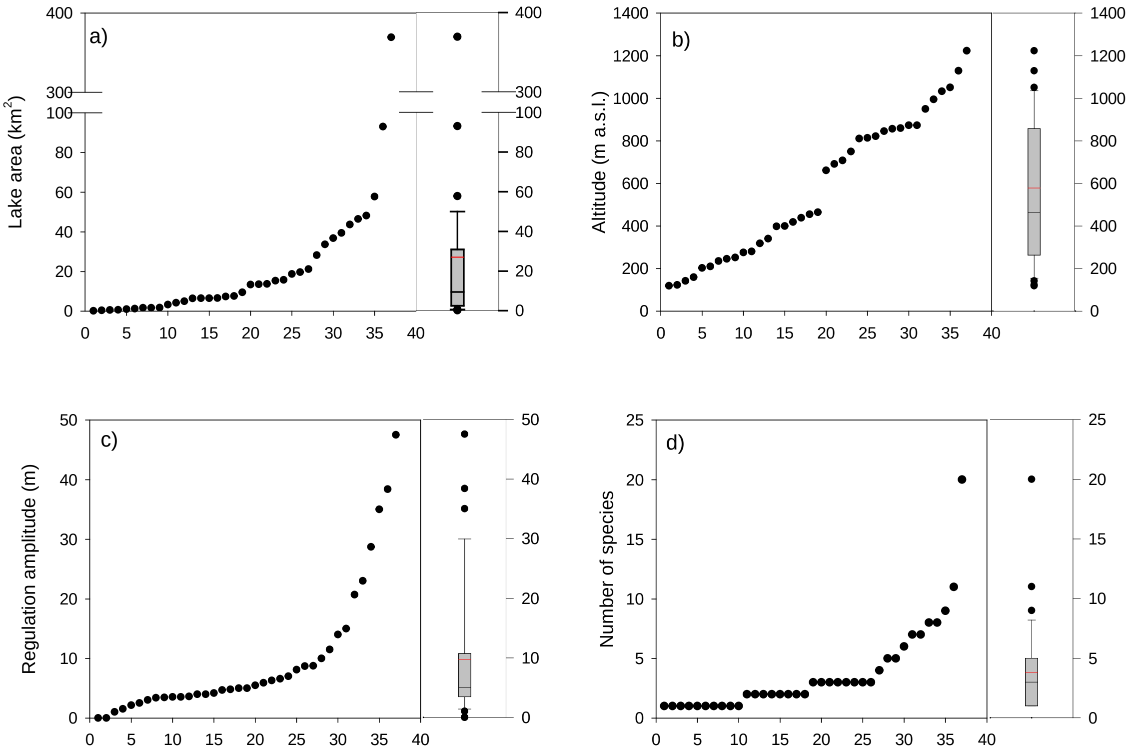

Figure 20. Increasing distribution of the 37 reservoirs according to a) Lake area (km^2), b) altitude (m a.s.l.), c) Regulation amplitude (m) and d) number of fish species. In each figure, the additional box-plot presents 50 % of the middle values (grey box), the median and average values (black and red line, respectively), the 10 % and 90 % percentiles (whiskers), and the outliers (dots).

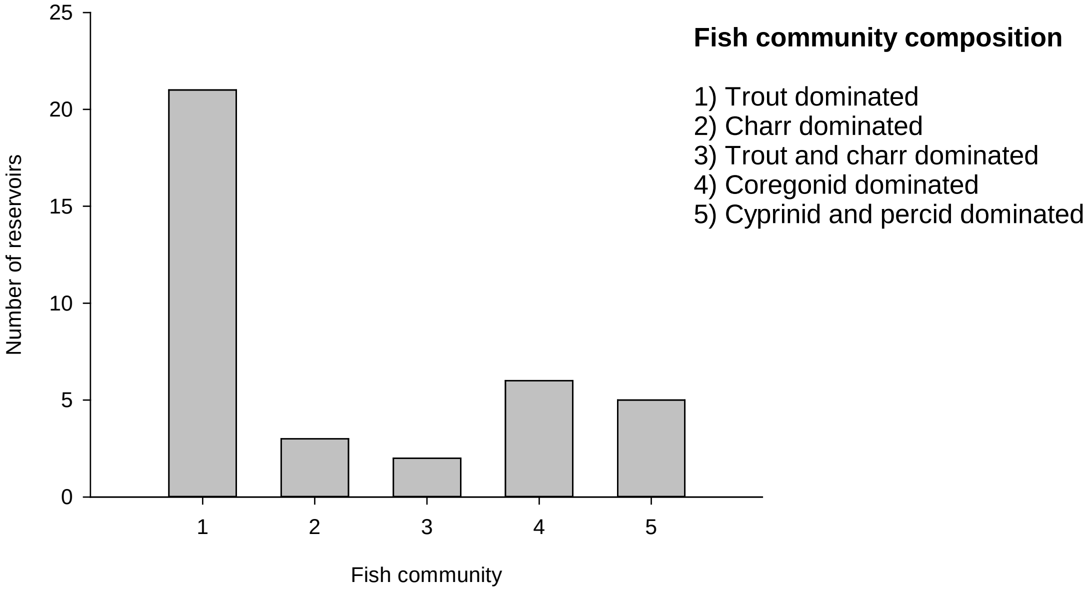

Figure 21. Fish community composition in the 37 reservoirs.

4.2 Types of mitigation measures reported by the County Governors

We used the categories defined by Glover *et al*. (2012) to further analyse the types of mitigation measures reported by the County Governors,. However, we have added some new categories where we found it relevant based on the data reported by the County Governors (Table 5). We have not included fish stocking or heavy fishing to reduce population density (M1 from Glover *et al*. 2012) in our analyses, since we do not consider such measures relevant for environmental design. When summarizing the main mitigation measures, each category of measures is recorded only once per hydropower reservoir. For example, if the same habitat measure is done in several inlets connected to a reservoir, it is recorded as one measure. If different types of measures are implemented in the same reservoir, they are all counted. We repeat that the data presented here only included measures targeting brown trout (including bleka), but see 4.3.4 for examples targeting other species.

Table 5. Overview of mitigation measure categories in hydropower reservoirs. The categories are adapted based on Glover et al. (2012). Habitat measures under M4 are split into measures in reservoirs and measures in inlet and outlet streams. Further, we have added more categories under M4 to adapt it to the incoming data. When habitat measures in inlets and outlet streams were unspecified, this is noted as M4e, while we have created the subcategories M4e-1 – M4e-5 to specify in those cases where more details were given.

	Main Category		Sub category
M2	Altered regulation pattern	M2a	Regulation amplitude
		M2b	Limited speed of water level reduction
M3	Lake in reservoir	M3a	Disconnected from reservoir
		M3b	Connected to reservoir
M4	Habitat measures in reservoirs	M4a	Establish vegetation along shoreline
		M4b	Addition of spawning substrate
		M4c	River entry measures
		M4d	Addition of substrate for shelter
	Habitat measures in inlets and outlets	M4e	Unspecified habitat measures
		M4e-1	Addition of spawning substrate
		M4e-2	Removal of migration barriers
		M4e-3	Addition of substrate for shelter
		M4e-4	Establishment of weirs
		M4e-5	Fish ladder in outlet dam
M5		M5a	Liming
		M5b	Nutrient addition
		M5c	Introduction of prey

Of the main categories, "habitat measures in reservoirs and rivers" (M4) was reported 42 times and thus constituted 71 % of the reported mitigation measures in hydropower reservoirs (Figure 22). Altered regulation patterns (M2) were reported in four (9 %) cases. One of the cases represented a measure to reduce an introduced and unwanted pike population by reducing the water level in springtime, while the other case was a water level adjustment to ensure that the landlocked salmon (bleka) adapted to spawn at deeper areas. All the five cases of "lake in reservoir" (11 %) were connected to the main reservoir by either fish ladders or rivers, thus falling into the category M3b, while no one reported cases of M3a ("lake in reservoir" disconnected from the main reservoir). The M5 "liming, fertilization and species introduction" category (9 %) constitutes of three examples of introduction of *Mysis relicta* and one case of nutrient addition. Liming has been done in numerous reservoirs in Norway due to acidification, but we assume that the County Governors did not consider this as a measure for hydropower impacts and thus did not report such cases.

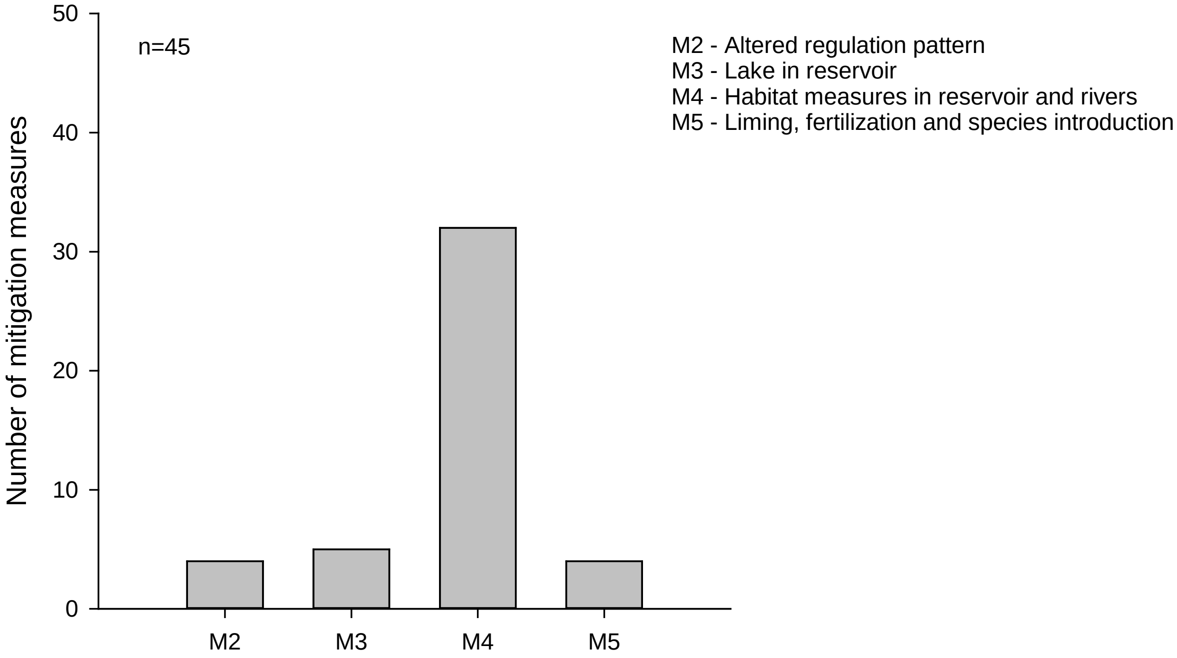

Figure 22. Distribution of main categories of mitigation measures reported from hydropower reservoirs in Norway. The number of mitigation measures are higher than the number of reservoirs due to more than one main category measure in some of the reservoirs.

If we split the 36 reported mitigation measures in category M4 (habitat measures) into subcategories, we see that only five cases (14 %) were conducted in the reservoir (M4b-M4d, Figure 23). These measures included addition of substrate for lake spawning trout and the land-locked salmon “bleka” (n=3), addition of substrate for shelter (n=1) and measures to ease entry to the river from the reservoir (n=1). The remaining 31 reported habitat measures (86 %) were conducted in inlet (n=24) and outlet streams (n=7). The seven mitigation measures in the outlets were all fishways at the outlet dam (category M4e-5). Of the habitat measures in inlet streams, most were unspecified (n=12); hence, we do not know which bottleneck(s) these measures were targeting. The remaining 12 measures in inlet streams included addition of substrate for spawning and shelter, removal of migration barriers to increase spawning and nursery areas, and establishment of weirs. The actual number of habitat measures are higher than presented here, since one type of measure is only counted once per reservoir, although in some reservoirs habitat measures are done in several inlet streams.

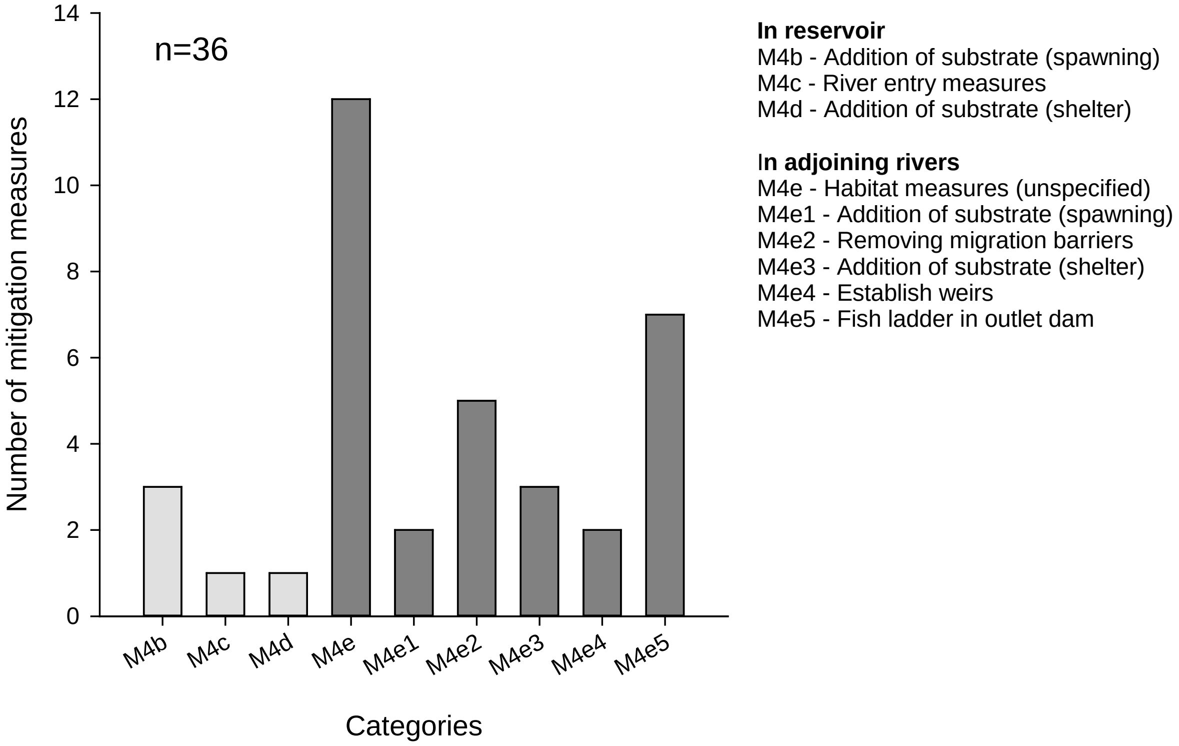

Figure 23. Distribution of different sub-categories of habitat measures reported from reservoirs in Norway. Light grey bars show measures done in the reservoirs while dark grey bars are measures done in inlet or outlet streams.

To see if there was a pattern regarding what type of reservoirs the mitigation measures were performed in, we plotted the types of mitigation measure against some easily available reservoir characteristics such as altitude, surface areas and regulation amplitude (Figure 24). It seems that habitat measures in reservoirs and adjoining rivers (M4) are represented in all kinds of reservoirs (Figure 24 a). For the measures altered regulation pattern (M2,) lake in reservoir (M3) and fertilization and species introduction (M5), the figures should be interpreted with caution due to few cases (Figure 24 a-c).

We also plotted the fish community in the reservoirs against altitude, surface area and regulation amplitude. As expected from the biogeographical pattern in Norway, we can see that the trout dominated reservoirs are located at a higher altitude than the more complex fish communities (Figure 24 d). The reported reservoirs with the largest surface area are dominated by coregonids, whereas the reservoirs with the highest regulation amplitude are dominated by trout.

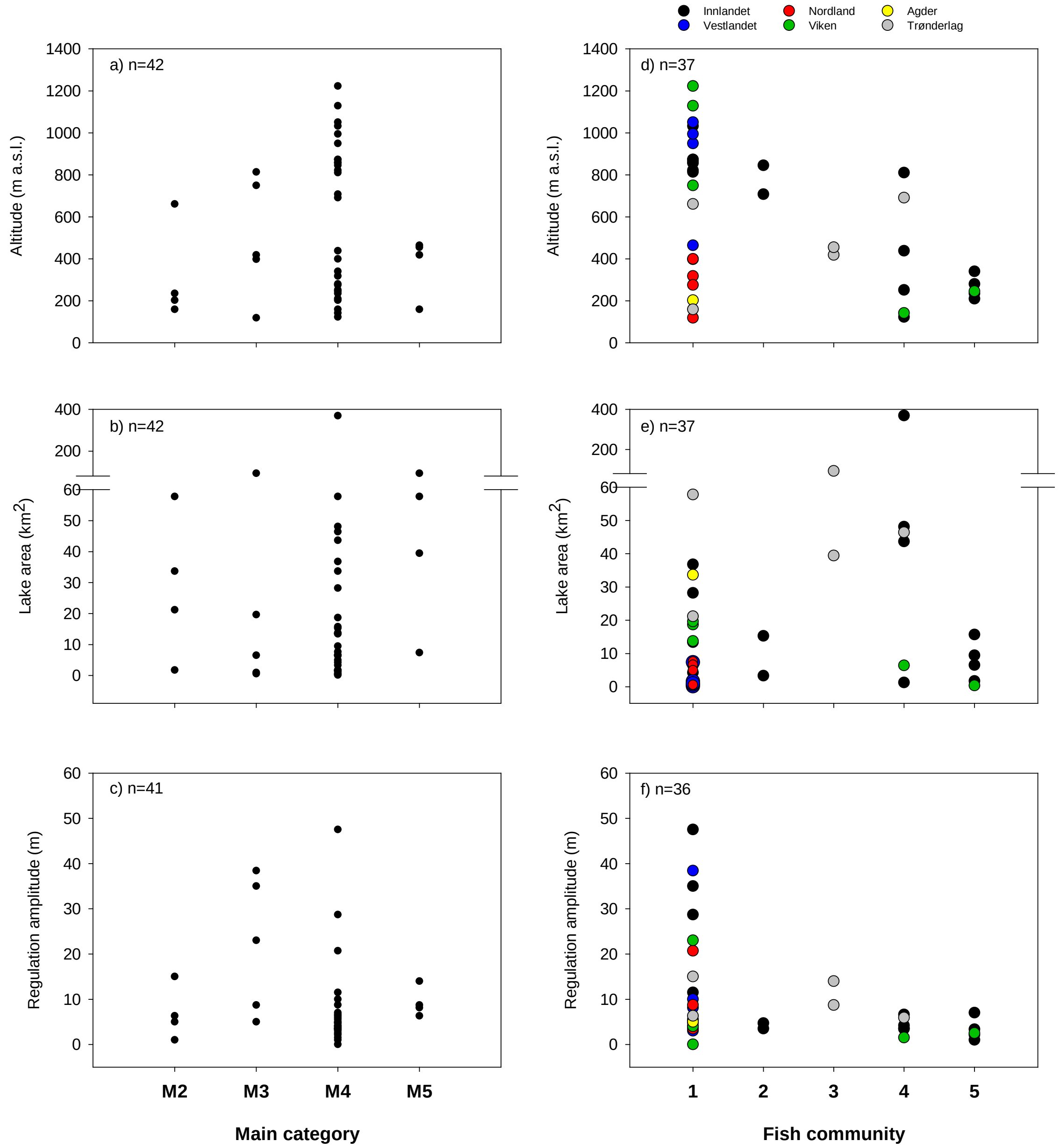

Figure 24. Distribution of main mitigation measure categories and fish communities along gradients of altitude (a, c), lake size (b, d) and regulation amplitude (c, f). M2 = altered regulation pattern, M3 = lake in reservoir, M4 = habitat measures and M5 = fertilization and species introduction. Fish community 1 = trout dominated, 2 = charr dominated, 3 = trout and charr dominated, 4 = coregonid dominated and 5 = cyprinid and percid dominated.

4.3 Mitigation measures implemented within a reservoir

As seen above, the majority of reported measures were performed in the inlet and outlet streams and not within reservoirs. Although important for the fish population in the reservoir, these measures are thus more similar to the design solutions already described in the handbook for salmon, because they are performed in rivers or streams. For the development of a handbook for reservoirs, we are mostly interested in measures performed within the reservoirs, as this is what we need to develop further for future design solutions. Therefore, we will describe the reported cases of true reservoir measures in more detail. There are five cases of habitat measures within the reservoir (M4a-d), four cases of altered regulation pattern (M2) and five cases of lake in reservoir (M3). As fertilization and introduction of species are associated with risks of unintended ecological changes in the full watershed, we consider such measures less promising for future design solutions and we have therefore not described the four reported cases within this category (M5). Introduction of non-native species is also illegal by the Norwegian law.

4.3.1 Altered regulation pattern

There are four reported examples of mitigation measures based on manoeuvring the water level. One example comes from **Løpsjøen** in Hedmark (Figure 25 A and B) where the brown trout population in the lake were exposed to predation from pike after turning a river section into a river reservoir. In order to mitigate predation from pike on brown trout and other environmental impacts, the water level has been lowered after the pike spawning period to increase egg mortality. Later in summer, the water level is lowered again in to increase predation pressure on pike yearlings due to decreased availability of vegetated shelter. The results from this water level manoeuvring experiment have not yet been evaluated.

The second reported case of altered regulation pattern is from **Byglandsfjorden** in Aust-Agder. Since the beginning of 2000, extensive stranding on the spawning areas of the land-locked salmon bleka was detected. To mitigate this impact, the hydropower company introduced a new regulation regime, by lowering the water level during the spawning period. After some water level adjustments, the result is that bleka now mostly spawn in areas below the low winter water level, where they also utilise man-made spawning areas created by addition of substrate (Barlaup *et al*. 2015). Thus, altered regulation pattern has successfully ensured that the target species spawn at deeper areas and thereby avoid stranding of eggs and fry.

In **Selbusjøen** in Trøndelag, the revised hydropower license valid from 2014 includes adjustments of the water level in autumn to ease access of spawning brown trout to the tributaries. This mitigation measure will be evaluated. The same measure is being practiced in **Gjevilvatn***et al*so located in Trøndelag.

4.3.2 Lake in reservoir

In **Innerdalsvatnet** in Hedmark, the hydropower company built a weir in the inner part of the reservoir, and established a 0.6 km^2 lake in reservoir in 1989 (total reservoir area 6.5 km^2). Due to this construction, a part of the reservoir is not impacted by unnatural water level fluctuations. This mitigation measure was primarily established to ensure shallow water areas for birds, but a by-pass channel was constructed to ensure a two-way passage of fish between the impacted and unimpacted (lake in reservoir) part of the reservoir. Surveys have confirmed good production of brown trout and important prey items in the unimpacted part, and that the mitigation measure was successful in terms of enhancing the brown trout population (Rognerud and Qvenild 2006).

Another example of a lake in reservoir is from **Pålsbufjorden** in Buskerud (Figure 25 C and D). The reservoir has a regulation amplitude of >24 m and large bottom areas dry out at LRWL. A weir was established in 2014 so that a part of Pålsbufjorden (called Rødtjennan) will only be regulated by 4 m. This will increase the watered areas at LRWL from 0.28 to 1.08 km^2**.** The lake in reservoir has two inlets that will ensure constant water flow. When the main reservoir in Pålsbufjorden is at HRWL, the weir at Rødtjennan will be 4 m below the surface and fish can pass freely. When the main reservoir is at LRWL, a by-pass channel/artificial river will ensure fish migration. This mitigation measure is not yet evaluated, but the increased watered area at LRWL is expected to increase food availability for brown trout (Brabrand *et al*. 2008).

Other examples of lake in reservoirs include **Limingen** (Trøndelag), **Kløvtveitvatnet** (Sogn og Fjordane) and **Vågøyvatn** (Nordland).

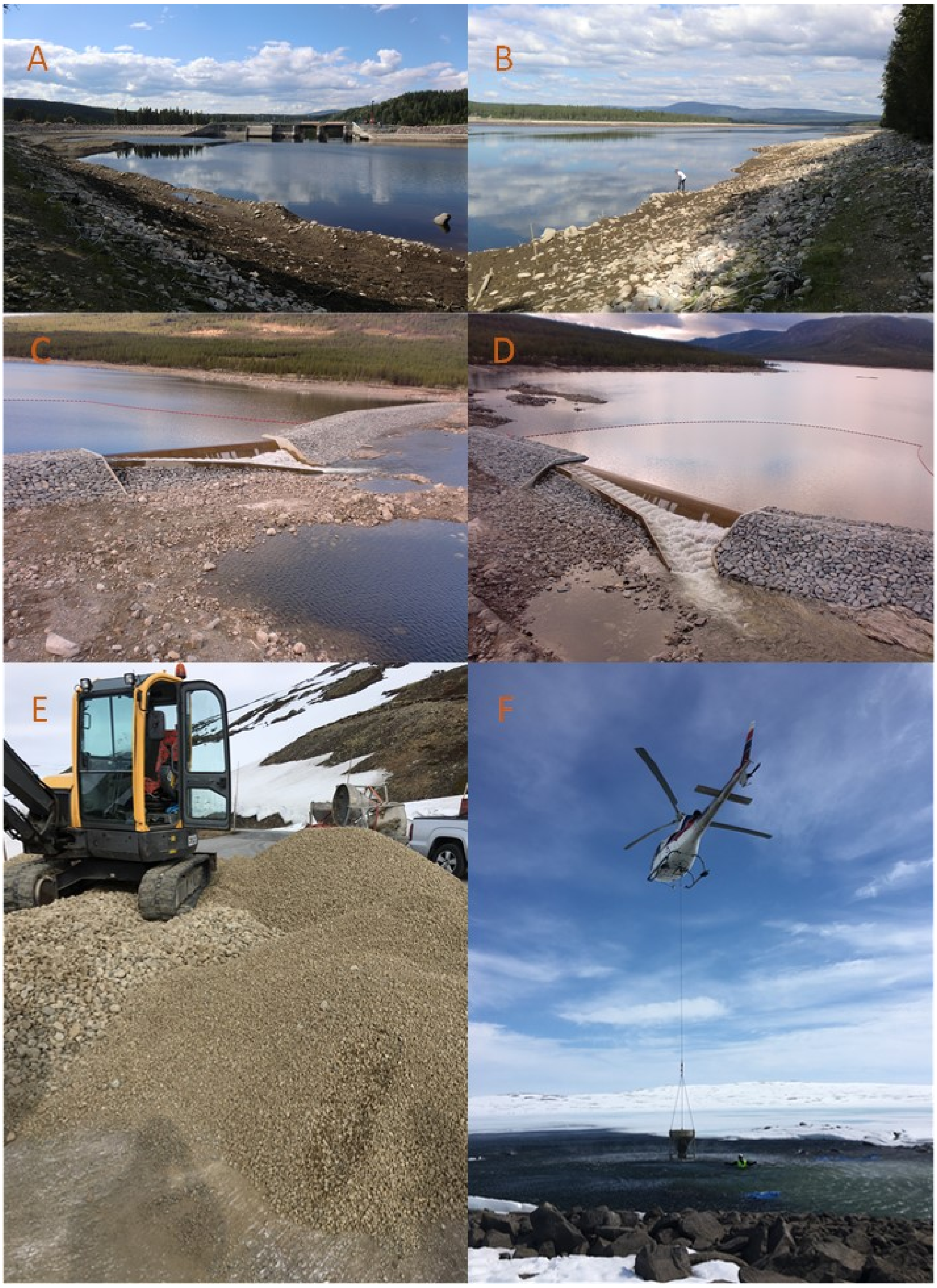
A
B
C
D
E
F

Figure 25. Examples of mitigation measures in Norwegian reservoirs. Pictures A and B are from Løpsjøen, showing lowered water level in an attempt to reduce recruitment of pike. Picture C and D show Pålsbufjorden and the "lake in reservoir" connected with a fishway to the main reservoir. Picture E and F show the addition of spawning substrate in Halnefjorden. Addition of larger rocks as shelter for brown trout in an inlet to Savalen (photos: G and H) and in the regulated zone of lake Savalen. (Photo credits: A, B, G-I: Trond Taugbøl, Eidsiva vannkraft AS, and C-F: Nils Runar Sporan, Numedals-Laugens Brugseierforening).

4.3.3 Habitat measures within the reservoirs

The County Governors reported three cases of addition of spawning substrate (M4b) for lake spawning trout and one case regarding the land-locked salmon “bleka”. In lake **Savalen** (Figure 25 G and H) in Hedmark, 522 m^3 of large rocks (30–80 cm) was placed within the regulated zone outside one of the spawning tributaries for brown trout. The idea behind this measure was to increase shelter for small-sized brown trout during low water level periods. In hydropower reservoirs (and unregulated lakes), rock shelters are often restricted to shallow areas along the shoreline. Follow up surveys and evaluations are in progress.

In **Aursjøen** in Oppland and Møre og Romsdal, water from a tributary spread and formed a braided stream in the regulated zone. To mitigate this it was created a thalweg to concentrate the water and ease the entry of spawning trout.

4.3.4 Mitigation measures targeting other species than brown trout

Among the reported data from the County Governors, a few examples of other species were included, more specifically measures targeting Arctic charr and European grayling (*Thymallus thymallus*). These examples were excluded from the statistics and figures above regarding brown trout, but are briefly described here. One example is from **Elsvatnet** in Nordland where spawning substrate were added for reservoir-spawning charr. In the same reservoir, there are plans to make a weir at the outlet to reduce unnatural water level fluctuations, but this measure is not yet implemented. Addition of spawning substrate with limestone for charr was also mentioned by the County Governors in Innlandet and Viken, but no specific reservoirs were reported, likely because these measures were not considered relevant for hydropower, but rather as a measure to mitigate acidification. For grayling, one example was reported from lake **Mjøsa** in Innlandet and Viken. Here, smaller habitat adjustments were done in the riverbed in the regulated zone of the lake to improve the access of grayling to their spawning areas in spring.

4.4 Additional examples of mitigation measures from the literature

Although we have been in contact with all of the County Governors during this project, there might be more examples of reservoir mitigation measures tested in Norway than what we are aware of. Since some mitigation measures may have been implemented many years ago and this work is not always archived and systematized, some measures might have been forgotten and therefore not reported. Further, there may be interesting cases from other countries that could be of relevance also in Norway. For example, Marttunen *et al*. (2006) reported that alteration of water level regulation practice, protection of erosion shores, restoration of lake habitats and revegetation in the littoral zone are more commonly applied in regulated lakes in Finland than in neighbouring countries Norway and Sweden. To supplement the data we received from the County Governors, we have searched for more reports and grey literature with Google. A full literature review of this topic would have been too time consuming for the present project. Nevertheless, without claiming that we have covered all relevant examples, we have tried to summarize the findings from the literature in Table 6. In this summary, we have also indicated what we believe are the pros and cons with the different types of measures, as well as provided references to examples when possible. Some of the mitigation actions, such as habitat restorations and modified water level regulation, can have multiple positive impacts on various biota and connected ecosystems. Despite being expensive in short-term, these solutions may support natural ecosystem processes unlike e.g. stocking of fish and fish prey items. Therefore, habitat restorations and clever water level regulation are often vital for reaching better ecological status in hydropower reservoirs. Most habitat measures will need to be repeated after a while, but some may last longer than others.

Table 6. Common environmental problems and solutions in hydropower reservoirs. Pros and cons of various mitigation actions are indicated, but they are highly variable and reservoir-specific.

Problem and mitigation	Pros	Cons	Reference / example
Reduced reservoir area and volume			
Reduced regulation amplitude	Increased productivity and biodiversity in different habitats and among various taxa	Expensive for hydropower producer	Brodtkorb 2000, Keto *et al*. 2008, Brabrand 2010, Rognerud and Brabrand 2010
"Lake in reservoir"; protection of a sub-basin or connected lake from regulation impacts	Protected areas can support viable communities and "feed" affected areas	Expensive, aesthetic problems, may disconnect habitats	Brabrand *et al*. 2008
Decreased water quality			
Reduced regulation amplitude and/or altered regulation timing	Improved physical, chemical and biological conditions, reduced sediment resuspension and homogenization	Expensive for hydropower producer	Brodtkorb 2000, Keto *et al*. 2008, Brabrand 2010, Rognerud and Brabrand 2010
Sediment traps or translocation (e.g. in inflow rivers from glaciers and peatland)	Decreased load of humus/clay/silt/etc. increases water quality, biological productivity and aesthetic value	Expensive, needs maintenance, structures may alter natural habitat linkages and processes	Schleiss *et al*. 2016
Planting of riparian and littoral vegetation	Buffers unwanted loading from the catchment, reduces shore erosion, provides habitat for aquatic and terrestrial biota	May introduce aesthetic issues and conflicts between users, not suitable in harsh conditions	Rørslett and Johansen 1996
Liming	Increased pH improves living conditions for various biota	Relatively expensive, must be repeated regularly	Anonymous 2016
Decreased habitat quality and connectivity			
Habitat restorations: adding gravel, stones, woody debris, artificial structures and/or "floating islands"	Supports fish recruitment and natural ecosystem processes, increases habitat for various biota	Expensive, maybe necessary to repeat regularly, potential conflicts between users, some actions not tested in Nordic countries	
Stream restorations and barrier removal (including man-made and potentially natural barriers)	Supports recruitment of migratory fish and natural habitat linkages and processes	May facilitate spreading of unwanted non-native species	Barlaup *et al*. 2008, Pavels *et al*. 2012
Reduced regulation amplitude and/or altered regulation timing	Supports vital aquatic-terrestrial linkages (e.g. transport of nutrients and carbon) and migrations of fish and other biota	Expensive for hydropower producer	
Planting of riparian and littoral vegetation	Buffers unwanted loading from the catchment, reduces shore erosion, provides habitat for aquatic and terrestrial biota	May introduce aesthetic issues and conflicts between users, not suitable in harsh conditions	Rørslett and Johansen 1996
Protection of shore erosion	Reduces habitat homogenization and sediment resuspension	May decrease habitat linkages and have aesthetical issues	

Decreased fish recruitment and growth				
	Stocking of juvenile fish	Increased density of valued fish, easy, inexpensive, controllable	Development of overcrowded/stunted fish populations, must be repeated regularly, competition and introgression with wild fish populations	
	Stocking of predatory fish	Improved growth of valued fish	Potentially unpredictable community and food-web impacts	Svenning *et al*. 2013
	Fish removal	Improved growth of valued fish	Costly, potentially unpredictable community and food-web impacts	Amundsen *et al*. 2015
	Fishing regulations (quota, size limits, protection of spawning areas and periods)	Supports natural recruitment, inexpensive	Potential public resistance, reduced recreational activities	
	Habitat restorations in reservoirs and rivers (e.g. substrate addition, barrier removal)	Supports natural fish recruitment and ecosystem processes	Relatively expensive, maybe necessary to repeat regularly	
	Altered regulation pattern (e.g. timing and amplitude)	Supports ecosystem productivity and processes, benefits various fish species and life stages	Expensive for hydropower producer	
	Introduction of new prey	Easy, inexpensive, increased fish growth	Potential unpredictable and negative community and food-web impacts	Aass *et al*. 2004
	Nutrient addition	Relatively easy and inexpensive, may support both benthic and pelagic productivity	May favour non-native species	Fjeld and Rognerud 2014, Rydin *et al*. 2008
	Planting of riparian and littoral vegetation	Supports aquatic-terrestrial habitat linkages, reduces shore erosion, buffers from unwanted loading	May have aesthetic issues and favour non-native species, not suitable in harsh conditions	Rørslett and Johansen 1996

4.5 Can future design solutions build on today's mitigation measures?

The survey among County Governors shows that there is limited experience with mitigation measures in reservoirs among the managers in charge. Of > 1200 Norwegian reservoirs, only 37 were reported to have known mitigation measures targeting trout. Among those 37, almost half were reported from the same region (Innlandet) while four regions had no measures to report. In addition to showing a low number of reservoirs, the survey also shows that almost all measures targeting reservoir fishes have been implemented in the streams and rivers (86 %). These measures can certainly be beneficial for a future handbook of environmental design in reservoirs. However, conceptually the measures targeting spawning areas in rivers and streams are in fact more similar to the environmental design already developed for salmon rivers. In this report, we have mostly focused on potentials for environmental design methodology within the reservoir itself, i.e. in the lake habitats. There are 14 cases of reported measures targeting trout within the reservoir (and a few targeting other fish species), and we find these cases particularly interesting and relevant for the development of a future handbook for environmental design in reservoirs.

It seems like most of the cases of reported measures within the reservoir could fit to the concept of environmental design. There are five examples of habitat-related measures, including spawning habitat for lake spawning trout and shelter for juvenile trout, four cases of altered pattern of water level fluctuations and five cases of creation of "lake in reservoir". However, some of these cases need proper evaluations before we know that the measures have had the desired effects. We believe that measures like these reported here are likely to improve fish populations in many Norwegian reservoirs. There are also some international examples listed in Table 6 that could be interesting to test in Norway. Given that *vannforskriften* requires that all waterbodies should achieve either good ecological status or good ecological potential, and the use of supplementary stocking as mitigation measure will be reduced, we expect to see an increase in environmental measures implemented in the reservoirs in the years to come. We recommend that true environmental design projects form the basis of future search for measures to implement in the reservoirs, which means that biologist, hydrologists, power producers and managers should work together. Although we may have some examples from the reported cases to learn from, it is important to find optimal ways to balance the need of the fish populations with the need for power production. We believe that the most important knowledge gap to fill prior to development of an environmental design handbook for reservoirs is to develop tools that can assist balanced decisions between the environmental needs and the power production, similar to those already developed for the salmon handbook:

> "*As a starting point habitat bottlenecks are addressed using habitat-related measures, and hydrologic bottlenecks using so-called "water use" initiatives (modifications to flow and water temperature). However, the best solutions commonly involve a combination of measures, where the costs linked to water use initiatives are weighed up against the benefits to the salmon population. In this way water is made available where it is most needed. In some cases, costly water use initiatives can be replaced by habitat measures, while in others expansions of the power production system may provide better opportunities for environmentally-designed water use. There are several tools available which can help us to achieve optimal water use design solutions. Such tools assist us in making balanced decisions – the right solution at the right time in the right place – and make it possible to estimate the impacts of different design solution scenarios*."
>
> Harby and Forseth, 2014, p.12

5 Conclusion

The aim of this report was to investigate the feasibility of developing a handbook for environmental design related to fish in reservoirs, similar to the one for salmon rivers. After going through available knowledge, sampling tools and methodology, we believe that it is achievable to develop such a handbook for reservoirs. We know quite a bit about the biological and physical processes in hydropower reservoirs and, as shown in Table 2 and Table 3, we have many available sampling tools that can be used in mapping of reservoirs. Further, the ongoing method development is rapid, particularly within image processing, air- and underwater drones and automatic monitoring devices. Therefore, **we believe it is realistic to identify bottlenecks and undertake a full diagnosis phase of environmental design based on today's knowledge**.

When it comes to the design solutions, there is a need for some method development before a handbook can be created. Our survey among County Governors showed that mitigation measures in reservoirs (within the lake) have only been tested in a few places, However, some of the reported cases certainly seem relevant for a design phase of a future handbook and should be investigated further. We strongly believe that it is feasible to develop suitable design solutions if we start working systematically in the reservoirs in accordance with the concept of environmental design, i.e. combining knowledge on biology, hydrology and power production. **The most important knowledge gap to fill before a full environmental design handbook for reservoirs can be created, is to develop tools that can assist balanced decisions between the environmental needs and the power production.** These tools must be developed through multidisciplinary collaborations between scientists, power producers and managers, in order to identify realistic solutions with minimal loss of power production.

The handbook for environmental design for regulated salmon rivers resulted from systematic multidisciplinary collaborations over more than 10 years. After the success of the handbook, a large research projects has recently been established to develop environmental design for inland rivers[11]. It is feasible to do the same for reservoirs, but we have to acknowledge that it will take some time and that sufficient resources have to be allocated to this work. Environmental design requires detailed work, and for example, more than 13 mill NOK are currently used to implement environmental design in the salmon river Mandalselva. If we were to map a given reservoir with the aim of identifying design solutions, we believe that the present level of knowledge and the available sampling techniques would allow us to do so. However, it would require some time, because the field sampling has to be more detailed than what has been standard surveys until today. The salmon handbook was built on many years of multidisciplinary research where experts within biology, hydrology, power production and management worked systematically together in selected case rivers and thereby developed new methods. **The best way forward for environmental design in hydropower reservoirs is to establish a similar multidisciplinary research project, where scientists, power producers and managers can work together, focusing on one or two reservoirs in detail and use this as a pilot.**

5.1 Recommendations

- Given the large variation among Norwegian hydropower reservoirs, it is not realistic to create a first handbook for environmental design that will be useful for all reservoir types. Hence, it would be useful to narrow the scope and identify some reservoir types that are of particular interest and start with method development targeting these reservoirs.

- It should be defined if the aim of a handbook for environmental design is to have viable and self-recruiting fish populations, or if the aim is to have fish populations that contain sufficient fish of desirable sizes for harvesting.

- The diagnosis phase for environmental design for reservoirs should consist of two parts: one based on data on fish populations and their main prey, and the other on hydrological and habitat data. In addition, the hydropower system must be described to understand the regulation effect.

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[11] https://www.ntnu.edu/web/hydrocen/environmental-design

- There is a need to implement a standard protocol for data collection in reservoirs. We suggest that the tools listed in Table 2 and Table 3 should be used in combination to form the basis of this protocol.

- All main lake habitats, i.e. littoral, pelagic and profundal areas, should be investigated when looking for the diagnosis, but the degree of details needed is not the same in all areas.

- Bathymetric maps should be created for all hydropower reservoirs in Norway.

- Use of temperature loggers at different depths over several seasons and years is needed to retrieve information on depth and development of the thermocline, time of spring and autumn mixing and duration of ice-cover.

- Several mechanisms for how habitat and hydrological features are limiting fish populations in reservoirs are poorly understood, and more research project targeting these issues is recommended. For example, we do not know properly which habitat characteristics best describe spawning areas for lake spawning fishes, or if and how density-dependent competition for shelter and littoral food may regulate fish production in Norwegian lakes and how this may vary between species. We also lack knowledge on individual fish movement between different habitats.

- The difference between HRWL and LRWL is not enough to evaluate the effects of the operational regime, i.e. the full water level fluctuation curve over time is needed.

- While common hydrological measures are used to evaluate hydropower impact on salmon in rivers (e.g. variation in water-covered area as a function of flow, changes in the lowest weekly average flow, changes in the frequency and magnitude of flooding events), there is not yet any consensus on which hydrological metrics to use when looking at ecological effects of hydropower in lakes. Hence, targeted studies of this are needed to create tools for a handbook for environmental design in reservoirs.

- Power production models must be used in combination with hydrodynamic models to simulate how different operational strategies influence water mixing and temperature within the reservoir.

- Although we have some examples of suitable mitigation measures in Norwegian reservoirs that can be used as a basis for future design solutions, it is a need to develop tools that can assist balanced decisions between the environmental needs and the power production.

- The best way forward for environmental design in hydropower reservoirs is to establish a multidisciplinary research project, where scientists, power producers and managers can work together, focusing on one or two reservoirs in detail and use this as a pilot.

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7 Appendices

7.1 Appendix 1 - E-mail sent to County Governors

«Hei!
Vi viser til informasjon som ble gitt på fagsamlingen i Molde i 24. mai. Vi har satt i gang et arbeid der målet er å lage en håndbok i miljødesign for fisk regulerte innsjøer. For å friske opp noe av det som ble presentert i Molde er det lagt ved noen Power Point bilder. Et ledd i dette arbeidet er å få oversikt over tiltak som er iverksatt i norske reguleringsmagasin og hvordan disse har virket. Se tekst fra NINA under.
Svarfrist: For å få framdrift i prosjektet er det ønskelig med rask tilbakemelding. Setter derfor fristen til 15. oktober. Svar sendes til Antti.Eloranta@nina.no

Mvh
Roy M. Langåker

NINA ønsker informasjon fra fylkesmennene:

Hei!

Vi i NINA holder på med et prosjekt finansiert av Miljødirektoratet der målet er å kartlegge hva som skal til for å kunne lage en «Miljødesignhåndbok for fisk i magasiner» etter mal av «Miljødesignhåndbok for regulerte laksevassdrag». En viktig del av dette prosjektet er å gjøre en kartlegging av alle tiltak som er prøvd ut i norske vannkraftmagasiner for å bedre fiskebestanden(e). Vi snakker altså ikke om settefisk, men om andre typer tiltak for å bedre forholdene for fisk. Det kan være fysiske tiltak som habitatforbedringer, terskler og liknende, eller kjemiske tiltak som tilsetting av næringsstoffer, eller biologiske tiltak som å tilsette Mysis. Vi har satt i gang et litteratursøk på dette og funnet noen relevante rapporter og dokumenter som beskriver slike tiltak i Norge. Men vi antar at det er flere magasiner der tiltak er forsøkt utprøvd som enten ikke er beskrevet skriftlig eller som kun finnes i dokumenter som er vanskelig for oss å finne. Derfor ønsker vi å ha tett dialog med fylkesmennene i dette arbeidet.
Vi ønsker innspill fra dere på to måter:

1. Først vil vi gjerne at dere tipser oss om alle skriftlige dokumenter dere kjenner til hvor tiltak i magasin er beskrevet. Det behøver ikke være rapporter som beskriver dette i detalj, det kan også være rapporter som egentlig handler om noe annet, men hvor det er et avsnitt som refererer til fysiske og kjemiske tiltak i magasiner. Det kan også være relevant med andre typer offentlige dokumenter enn rapporter, for eksempel brev, filer som viser foredrag, møtereferater etc. Hvis dere har tips til slike dokumenter, send dem til Antti.Eloranta@nina.no så raskt som mulig.

2. Litt seinere i prosjektet, når vi har gått gjennom det skriftlige materialet, så vil vi gjerne ha samtaler med dere for å få mer informasjon enn kun det som er skriftlig dokumentert. Vi kommer derfor til å ta kontakt med dere for å avtale tidspunkt for en telefonsamtale. Vi kommer tilbake til innholdet i disse samtalene seinere og enn så lenge er det ikke noe dere trenger å tenke på.

Vennlig hilsen Antti Eloranta og Ingeborg Helland»

7.2 Appendix 2 – Template for County Governor informants

Environmental design for brown trout in hydropower reservoirs – template for informants

Main objective: Get an overview of mitigation measures carried out in hydropower reservoirs aiming to enhance conditions for brown trout (included spawning- and nursery rivers). Both physical and hydrological measures are relevant.

Basic questions and information:

- Informant at The County Governor:
    - Name
    - Position
    - County

- How does the informant grade his own knowledge on the subject (scale from 0-3, where 0=no, 1=little, 2=average, 3=good.
    - If knowledge is 0 or 1, do you have candidate informants?

Repeat questions in the box for each hydropower reservoir

- Hydropower reservoir/lake
    - Name of the lake
    - NVE running number
    - Water level amplitude
    - The name of the hydropower company?
    - What fish species are present?
    - Imposed or voluntary mitigation measure?
    - Subject to fish stocking? ?

- What mitigation measure (may be several) and why carried out (including spawning- and nursery rivers)
    1. Ex. addition of spawning substrate
        - Is the mitigation measure evaluated?
        - Are there any reports?
        - Information about financial costs regarding the mitigation measure

- Are there planned any forthcoming mitigation measures in the County?

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