SUSHP 2023

PROCEEDINGS

Sustainability in Hydropower 2023

- Ecological mitigation, best practices and governance

Trondheim, Norway, 13–15 June 2023

Organizers:

HydroCen

NTNU | Team Hydropower

Swedish Agency for Marine and Water Management

Norwegian Environment Agency

In collaboration with:

TrønderEnergi

VATTENFALL

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INTRODUCTION

Hydropower is still by far the largest form of renewable and low-carbon energy source. Hydropower contributes with large volumes of clean energy and flexibility into an energy system with a gradually larger share of intermittent sources, such as solar and wind power. At the same time, there are a set of sustainability challenges associated with hydropower projects and their impacts on the natural environments, such as modification of flow regimes, barriers, and fragmentation, affecting migration of species and continuity of sediments and nutrients, that need to be properly addressed. These challenges require contributions from experts with a wide set of competences, and involve different sectors and authorities at various levels, engagements from the industry, interest organisations as well as researchers and consultants. As such, improving the sustainability performance of hydropower ask for truly integrated and coordinated efforts and actions.

The 2nd International Conference on Sustainability in Hydropower took place in Trondheim, Norway, in the period June 13th – 15th, 2023, with almost 200 participants. The conference was a hybrid of physical and on-line participation, with the majority of the attendees participating physically. The conference was a follow up of a previous sustainable hydropower conference arranged in Northern Sweden in June 2019, hosted by Swedish Agency for Marine and Water Management (SWAM) and the County Governor of Norbotten.

The conference in Trondheim focused around three main topics:

- Essentials for planning successful improvement of environmental values while securing the benefits of hydropower production.
- Emerging best practice within ecological mitigation measures and best available technologies.
- Governance with regard to sustainability, resilience, biodiversity and climate change, both in Europe and developing countries.

This is the proceedings from the 2nd International Conference on Sustainability in Hydropower, 2023, and contains abstracts submitted to the conference that was later presented orally or as posters. All abstracts have undergone review by a scientific committee.

We would like to thank all the contributors and participants of the conference that took place, and we are looking forward seeing you again in Austria in 2025!

Tor Haakon Bakken (Prof.)

Norwegian University of
Science and Technology (NTNU)

Cochair SusHP 2023

Jo H. Halleraker (Chief Engineer)

Norwegian Environment Agency

Chair Sus HP 2023

Visit the conference website:
ntnu.edu/sushpconf

Opening plenary

Tuesday 13. June 2023

SUSHP 2023

Sustainability in Hydropower 2023

Emerging policies, regulations, and international sustainability standards

Opening Plenary welcoming presentation by Anders Iversen (National Water Coordinator, Norwegian Environment Agency).
Photo: Jo H. Halleraker

EU Hydropower balances targets for climate and environment

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ABSTRACT: Against the backdrop of the war in Ukraine, the European Union (EU) faces the complex challenge of balancing energy security, affordability and competitiveness while making the transition to a decarbonised economy. Simultaneously, the world is facing an unprecedented environmental crisis. Climate change is no longer a distant threat but a pressing issue that requires immediate action. Biodiversity loss is proceeding at an alarming rate, further accelerated by rising temperatures, which will become the main cause of habitat and species loss by 2050.

To counter these crises, the EU is pursuing the massive expansion of renewable energies, especially wind and solar power, as part of its Green Deal strategy. However, integrating the variable electricity generation of these two technologies requires increased flexibility to ensure a balanced and reliable power system. Basically, a broad range of technologies is available to cover these needs. In this context, Hydropower stands out, as it offers flexible generation with its reservoirs and related run-of-river plants and electricity storage through its pumped storage facilities (i.e., flexible consumption and generation), on a large scale and in a sustainable manner.

In addition to contributing significantly to climate change mitigation, the European hydropower sector is committed to taking feasible measures to minimize its impact on nature when also acknowledging its positive contribution to meet social needs. How this is implemented and what innovative and integrated solutions that benefit nature and the climate look like is demonstrated in Eurelectric's Power Plant Project.

Beyond climate and environment, hydropower plants provide further multi-purpose benefits for people, communities and the economy, such as supporting the mitigation of floods and droughts, providing water for drinking, irrigation and industrial needs as well as promoting tourism and navigation.

Green for real? Have you asked the eel?

Åsa Renman

Water coordinator for The Norwegian Biodiversity Network (Sabima), The Norwegian Association for Outdoor Organisations, The Norwegian Hunters' and Anglers' Association, WWF Norway, The Norwegian Trekking Association and Friends of the Earth Norway

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ABSTRACT: Since the introduction of the water framework directive (WFD) in Norway, this group of Norwegian NGOs has cooperated closely on a wide variety of freshwater conservation and restoration issues. The substantial impact of Norwegian hydropower is one of our main concerns.

The presentation addresses our experience with working for improving the environmental status in hydropower affected rivers. This mainly involves our participation in public processes regarding the review of license terms and making use of the legal toolbox which the Norwegian government claims ensures the implementation of the WFD.

Our main message is that sustainability cannot be reduced to frivolous formalities where the modus operandi, to put it bluntly, is to market itself as green, without requirements for necessary corrective environmental measures and modern environmental terms for operation.

For further reading about the weaknesses we have identified regarding the implementation of the WFD and hydropower affected waterbodies, please see: https://www.sabima.no/ber-esa-vurdere-norsk-vannkraft/

We welcome the EU Taxonomy with its Do No Significant Harm-criteria, which are aligned with the recognition of the need to conduct ourselves with regard for addressing the global nature crisis. It is also aligned with Norwegian civil society's political recommendations to meet the Montreal goals, recently published in a joint report[1], as well as in a report for nature positive business by Sabima and PwC[2].

[1] *For naturen* (9 June 2023) Report with proposals for political, regulatory and structural changes needed for Norway to reach the goals in the Global Biodiversity Framework, by BirdLife Norway, Norwegian Forum for Development and Environment, Future in our hands, Norwegian Friends of the Earth, Sabima, Spire and WWF Norway
https://www.sabima.no/arrangement/vi-lanserer-for-naturen/

[2] *Naturpositiv ledelse - En praktisk veileder til arbeid med naturrisiko i næringslivet* (2023) PwC and Sabima (A practical guide for nature-positive business)
https://www.pwc.no/no/nyheter/naturpositiv-ledelse-rapport-digital.pdf

Plenary 2

Tuesday 13. June 2023

SUSHP 2023

Sustainability in Hydropower 2023

Lessons learned, regionalwise best practises and sustainable management of water

An Overview of US Hydropower Viewed Through the Lens of EU Taxonomy for Sustainable Activities

Dr. Brenda Pracheil, Fisheries Biologist, Pacific Northwest National Laboratory, Governing Board Chair, Low Impact Hydropower Institute (United States)

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ABSTRACT: This talk will provide an overview of US hydropower regulation including current trends and future forecasts of how environmental impacts of hydropower are being assessed and mitigated in the US and how these solutions map to the EU Taxonomy for Sustainable Activities. The United States has regulatory requirements explicitly addressing Taxonomy objectives on the sustainable use and protection of water, pollution prevention and control, and protection and restoration of biodiversity and ecosystems but does not yet name climate change mitigation or adaptation and transition to a circular economy as in regulatory requirements. However, voluntary participation in meeting enhanced environmental standards that are driven by market incentives in some areas may help some US facilities address additional objectives. Hydropower regulation in the United States is driven by individuals and governmental and non-governmental organizations that provide input on what and how environmental impacts should be assessed and mitigated. Participants in the regulatory process are beginning to drive US regulations closer to meeting EU Taxonomy objectives, particularly those related to climate change.

Overview of mitigation measures implemented in France to reduce ecological impacts of hydropower

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ABSTRACT: Around 2,500 hydroelectric power stations in France are spread over 250,000 km of rivers. With an installed capacity of 25 718 MW and a mean output of 58 TWh (which represents 12% total consumption), France is the third largest European producer of hydroelectricity. A great number of small hydropower plants are located in the headwaters and generate a low output whereas a low number of large hydropower plants generate a high output.

The main ecological impacts of hydropower plants concern the change in aquatic habitat due to the creation of an impoundment, the modifications of flow regime (minimum instream flow, hydropeaking) and the alteration of fish and sediment continuity. Environmental conditions and the characteristics of hydroelectric schemes vary widely across the country. Their combination generate ecological impacts of very varied nature and intensity. The will to maintain a balance between preserving a good ecological status in hydro-systems and providing for multiple uses of water has been made clear in French legislation.

This talk will give, for each type of ecological impact, an overview of 1) regulations in France to reduce these impacts, 2) mitigation measures implemented to respect these regulations 3) the tools and research available to guide their implementation. Some examples of good practices which go beyond regulatory requirements will be given for different study cases.

In conclusion, a good diagnosis is necessary to identify appropriate actions. Mitigation measures have to be adapted to specific environmental conditions, take into account the processes which operate at different spatial scale, the natural variability of ecosystems and account for climate change. The future challenge is to develop technical and environmental solutions which allow for increased flexibility of production and reduced ecological impact in a context of climate change and in respect of social needs.

Balancing increased capacity and flexibility with environmental values in a proposed redevelopment of an existing hydropower scheme

William Elvey, Hydro Tasmania, Marie Egerrup, Hydro Tasmania, Lois Koehnken, Technical Advice on Water

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ABSTRACT: The Tarraleah hydropower scheme is one of the oldest hydropower schemes in Tasmania, Australia. Water is diverted from Lake King William to the power station via two canals and bypasses 31 km of the River Derwent downstream of the lake. Much of the scheme is more than 80 years old and many of its assets are nearing the end of their operational life. The scheme needs significant investment to ensure it can avoid risk of failure and support the transition to a renewable dominated National Electricity Market reliably and safely well into the future.

The River Derwent downstream Lake King William has a highly regulated and reduced flow regime. The altered flow regime and the barrier of the dam has reduced the supply and mobilization of riverbed sediments. Reduced high flow events have also allowed terrestrial vegetation to encroach into the side and mid-channel bars. In combination, these factors have resulted in channel narrowing, armoring of the riverbed and a reduced area of active channel.

Hydrological modelling indicates that the spill regime downstream Lake King William would be further reduced in frequency and magnitude during operation of the proposed redeveloped scheme. The key environmental values protected by legislation identified for the river reach below Lake King William are a 23 km reach within the Tasmanian Wilderness World Heritage Area (TWWHA) and habitat for a threatened plant species *Barbarea australis* (native wintercress). *Barbarea australis* is an opportunistic riparian coloniser in the Brassicaceae family and is endemic to Tasmania. This species appears to rely on disturbance, particularly flow disturbance, to turn over riverbed sediments to create suitable conditions for its establishment. Without mitigation, a reduced spill regime could potentially impact TWWHA values, including habitat for *B. australis,* through reduced mobilisation of bed and bank sediments; increasing the rate of encroachment by terrestrial plants and accelerating contraction and armouring of the channel; and lower the quality of instream habitats for aquatic species. A hydraulic model was developed to determine the flow requirements to mobilise bed and bank sediments to maintain habitat for *B. australis* and slow terrestrial encroachment. The model outputs and historical spill data were used to propose flow releases to mitigate the impacts of the predicted reduced spill/high flow regime. The proposed mitigation measures increase the magnitude and frequency of spill events that are likely to maintain the existing TWWHA values and *B. australis* habitat requirements. The performance of the hydraulic model is currently being validated by field trials assessing rock movements under various flow events. It is also proposed to monitor and apply adaptive management relating to the size of the flow releases to ensure they are effective. These targeted mitigation measures offer a balance that allows more flexible operation without compromising existing environmental values in a regulated system.

Mitigation measures revisited – environmental effects, costs and endurance

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ABSTRACT: Two decades after the release of the Water framework directive (2000) and several years after the Norwegian Environmental Design Handbook (2013), the Mitigation Measures Handbook (2017), and the Best Practice Guidelines for Fishways (2018), we have gained more field experience regarding the performance of environmental mitigation measures, fishways and river restoration.

We are presenting data on the costs, maintenance, ecological effects, and endurance of the following measures used to mitigate the environmental effects of hydropower: sediment cleaning (ripping), spawning gravel augmentation, boulder placement, riverbank revegetation, management of submersed vegetation, upstream fishways, downstream fish passages, reduction of gas supersaturation, reduction of stranding areas during hydropeaking, evaluation of environmental flows, temperature management, dam and ground sill removal, nature-based bank and channel stabilization, nature-based climate adaptation, sediment management, reintroduction of large woody debris, and river restoration.

These results provide valuable cost-efficiency data for the ongoing relicensing of hydropower in Norway, for hydropower mitigation measures in general, for the implementation of the Water Framework Directive, the UN Decade of Ecological Restoration, climate adaptation, and the EU sustainability taxonomy. Different concepts of planning mitigation measures are discussed, such as environmental design, river restoration, river typologies, adapted baselines and nature based solutions. The results will contribute to defining "best practices" and paving the way towards greater sustainability in hydropower.

Good governance and long-term changes of the water resources systems

Effects of planned hydropower dams and barriers on river connectivity in the Balkan region

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ABSTRACT: Hydropower is at the forefront of renewable energy production and will strongly contribute to decarbonise energy production. However, dams have different impacts on the river system, including the disruption of river continuum and the alteration of the natural connectivity. Most of the unexplored hydropower production capacity in Europe is in the Balkan region, home of some of the best-preserved rivers in the continent. The construction of approximately 3000 hydropower dams is planned in the area in the near future, which leads to a conflict between different societal needs, environmental laws, sustainable development targets. In this work we analysed the effects of the planned hydropower dams on river connectivity (or fragmentation), with the aim to produce reliable information that can assist in minimizing conflicts and impacts. We applied four metrics: barrier free length (length between pairs of consecutive barriers in each basin), I_{max} (longest barrier free segment in each basin), BFL_{Max} (I_{max} divided by the total length of the basin) and the DCI (dendritic connectivity index) for potadromous fish. We analysed the existing fragmentation of the Balkan region and of other European areas using ground-truthed data, highlighting how barriers of any type are 2.2 times lower in the Balkan region. We compared the existing fragmentation with 8 different dam construction scenarios and observed that any scenario would result in loss of connectivity, with the largest loss corresponding to the construction of all barriers (~47% of the barrier free length). Interestingly, building only dams for large hydropower plants (> 10MW) will lead to the smallest loss in connectivity, and the largest increase in hydropower production, while small dams will cause a large increase in fragmentation that will not correspond to a large increase in hydropower production (see figure 1). We discuss the indications derived from our scenario analysis based on river connectivity, but a comprehensive analysis should consider that large dams might also have other physical/ecological consequences.

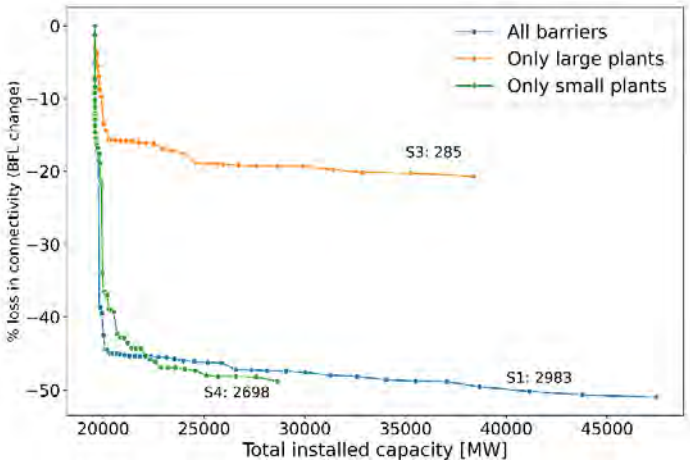

Figure 1 Loss in river connectivity (expressed as % loss in BFL) with increased installed hydropower capacity under three different scenarios: all barriers are constructed; only large plants are constructed; and only small plants are constructed.

We also analysed the contribution of individual plants and barriers to energy production, and their effect on river connectivity, which helps to identify the most impacting and less productive barriers which construction should be avoided. With our work we want to encourage decision and policy makers to consider the river connectivity dimension, and to assist in the identification of which plants and barriers should be prioritized, in order to maximize production and minimize the impact on river connectivity to improve hydropower sustainability.

Climate change in the context of Environmental flows and changed hydrology in three basin areas in Sweden

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ABSTRACT: Hydropower plays a key role in the conversion into renewable electricity systems, but affects ecosystems negatively, that call for environmental-flow assessments to enhance the ecological status of river systems. Environmental flow assessments need to consider for climate change in the context of changed hydrology that affects both hydropower operation and riverine ecosystems. In collaboration with the hydropower company Statkraft in Sweden, we assessed how environmental flow scenarios benefitting the regulated ecosystem along with changed electricity production in the basin areas of the Ume River, Ljungan River and Lagan River in Sweden. Runoff until 2040 was projected to increase in all basin areas (average per year 2.6%, 2.6%, 1.3% respectively) leading to a 2.2% increase in hydropower production until 2030 in the Ume River, 3.1% and 1% respectively in the Ljungan and Lagan river until 2040. We modelled environmental flow scenarios (12 in the Ume River, 13 in the Ljungan River and 12 in the Lagan River). All scenarios for each basin area covered ecological functions such as base flow, more natural water-level variation, opportunities for fish migration and minimum discharge to bypassed reaches. Our results show that implementing environmental flows will result in lower hydropower production losses in 2030/2040 than with present runoff (1981-2010). The most cost-effective environmental flow measures were introducing restrictions against zero flow events and start/stops of turbines. Restrictions against zero flow events caused an annual loss of 0.5% of hydropower production in the Ume River, a gain of 1% in the Ljungan River and 1-2% in the Lagan River, without consideration of effects on the balancing and regulating power. The environmental flow measures are projected to increase ecological function in lotic habitat, 348 ha in the Ume River, 321 ha in the Ljungan River and 362 ha in the Lagan. In addition, we argue that restrictions against zero flow events and turbine tarts/stops would decrease the intensity of hydropeaking and improve conditions for lotic species by voiding periods of standing water, which is an unnatural phenomenon in a river. To conclude, our example demonstrates the feasibility of introducing environmental flows with large benefits for riverine biodiversity, while sustaining hydropower production in a future climate.

Methods, indicators and solutions for sustainable hydropower

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ABSTRACT: Planning, building and operation of hydropower must include considerations of technical, economic, environmental and social aspects in order to meet sustainability criteria. To address the environmental needs in a regulated river, we have developed the environmental design methodology. The method has previously been developed for only one species, Atlantic salmon, and it has been applied to several regulated rivers with hydropower and important salmon stocks. We are now developing similar methods for other species, activities and services.

The objective is to improve licensing, operation and mitigation measures in regulated rivers with hydropower to meet sustainability requirements.

We have defined a number of species, activities and services it is important to consider reaching sustainability in Norwegian rivers, adapted to the local conditions: the aquatic species salmon, trout, char, grayling, eel, river mussels, dune tiger beetle and benthic macroinvertebrates; the activities kayaking, swimming, fishing and aesthetics, the special nature type river delta as well as the services flood control, water supply and flexibility and energy services to the grid.

The first step is to establish a diagnosis on how hydro-morphological factors that are impacted by hydropower and river regulation. Key indicators for each species, activity and service about how they are impacted by alterations in hydro-morphology are defined and assessed. Typical indicators are changes in low flow and floods, water-covered area, water depth, water velocities, sediments, substrate, water temperature, water vegetation, riparian vegetation and the presence of barriers. Metrics to assess key indicators are developed for each species, activity and service to be able to identify effects and bottlenecks.

We have also developed a suggestion for classification of hydro-morphology to be used for Norwegian river and lake water bodies in the implementation of the EU Water Framework Directive. This method have been tested by researchers and water managers, and the method "HyMo 1.0" is now ready for use by the authorities. The HyMo 1.0 method will give fundamental indicators of how the hydromorphology is altered in hydropower rivers. Together with the environmental design methodology, it is possible to identify cost-effecitive mitigation measures to obtain sustainability in hydropower.

This presentation will outline the HyMo and Environmental Design methods, and we will show some examples of use.

Mapping the natural values and ecological rehabilitation potential of Sweden's bypassed river reaches

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ABSTRACT: One of the primary impacts of dams and regulation on river systems is the loss of rapids and water falls, as the fall height is used for electricity production in hydropower stations. What is the ecological state of such reaches, and what can be done to improve their ecological conditions? To address these questions, we created a database of all bypassed reaches in Sweden, that is, river sections where discharge has been diverted to hydropower stations, which leaves the original river channel dry or with reduced discharge. There were 972 bypassed reaches meeting our criteria, and the majority of these lack any mandates on minimum flow release: Out of 622 reaches with flow data, 481 lacked mandated minimum flow release. The 137 bypassed reaches with minimum flows had an annual flow averaging only 3.6% of their pristine mean annual discharge.

The mean slope of the channels of the bypassed reaches was relatively high (3.6%), and they generally correspond to runs and rapids in terms of flow velocity. The average length of bypassed reaches was 1,317 m, with a median length of 319 m, the distribution being skewed with many short and fewer long ones. The majority of them were positioned in the lower reaches of catchments, in stream order 1 and 2 counting from the mouth. The bypassed reaches had a lower proportion of rheophilic fish species and lower fish abundance compared to reference sites in free-flowing rivers, according to electrofishing data. Bypassed reaches with minimum flow release had fish communities with higher proportion of rheophilic fish species, higher abundance of fish, and more fish species per site compared to bypassed reaches with no minimum flow release. Furthermore, the proportion of rheophilic over lentic fish species, fish abundance as well as species richness of fish increased with increasing magnitude of minimum flow release, with diminishing returns at higher flow levels.

Collaboration among stakeholders (including hydropower managers, authorities, consultants and NGOs) is key to be able to select which bypassed reaches to be targets of ecological rehabilitation, and to implement ecological rehabilitation measures. We present a framework to facilitate the process, and discuss the competences needed for a successful process, as well as a methodology going from mapping, to analyses of impacts and needs, and projection of potential benefits of ecological rehabilitation options. To facilitate making decisions on the magnitude of minimum flow release, we present a list of ecosystem states or functions, and the aspect of the flow regime needed to maintain them. This can help determining the flow needed to obtain specific ecosystem functions or states, or conversely, given flow, what ecosystem functions and states are realistic to achieve.

Multidecadal trends in brown trout (*Salmo trutta*) populations in regulated and unregulated river

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ABSTRACT: Most studies that have examined temporal trends in freshwater fish populations have rarely focused on headwater streams. In the present study, we jointly examined sections regulated and unregulated by dams to investigate shared or divergent temporal patterns in (i) a panel of stream-dwelling brown trout (*Salmo trutta*) populations and (ii) environmental variables known as environmental drivers of trout population dynamics (water temperature, stream flow, current velocity and habitat suitability). We conducted trend analyses of brown trout populations in 36 stream reaches spanning a diversity of French geographic areas (lowland and mountain streams). Of these reaches, 19 are located in a bypass section, with part of the stream flow diverted by a dam and are subject to a minimum flow (or residual flow). These reaches were regularly sampled over the period 1990-2020 for a total of 752 fish samplings.

General temporal trends in environmental variables and densities of three trout cohorts (i.e. young-of-the-year, juveniles and adults) were assessed using a meta-analysis framework. This method consists in a weighted meta-analysis performed on each environmental and trout variable using Mann-Kendall trend statistics (S) computed on each time series as “effect sizes”. This non-parametric method is used to statistically assess if there is a general monotonic upward or downward trend in the studied variable over time and over the entire dataset, without this necessarily being linear.

We found that the average annual temperature of these streams has significantly increased by a median of +0.21°C per decade. This upward trend was observed in most of the studied reaches, indicating that global drivers are probably involved. Spring, summer and fall water temperatures also showed a general significant increase. Analyses of stream flow revealed only a few significant trends, including a general increase in median values in spring and a general decrease in fall. Trends in current velocity were stronger and more significant than those found for stream flow.

A significant general decline in adult trout densities was observed, although disparities between geographic areas were found. No significant trend was found in the densities of the younger

cohorts. The trends in trout densities found in bypass sections and in reaches without hydrological modifications were not significantly different. The general decline in adult densities is likely due to multifactorial effects, in relation with the environmental changes observed during the study period, but also probably in relation to other factors not assessed in this study (e.g., predation, disease, water quality…).

Our results highlight the need to maintain long-term monitoring of trout populations, which should ideally be combined with extensive environmental monitoring. This would allow appropriate and efficient management measures to be taken in both regulated and unregulated sections to improve the living conditions of trout populations in a context of global change.

Long term changes in riverscapes in rivers regulated for hydropower.

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ABSTRACT: Development of storage-based hydropower alters flow regimes in rivers and thereby induces changes in seasonal distribution flow distribution, changes water covered areas of rivers, reduces the natural flood regime, and alters sediment transport mechanisms. The alterations in the natural flow regime and processes associated with flow can have long term effects on riverscapes, changing the distribution of habitat types and cause loss of important habitat seen on longer time scales which again influence biodiversity in regulated rivers. Several endangered riparian habitats need more attention and restoration efforts to enable a more biodiversity positive development of Norwegian riverscapes, in line with UN IPBES and to reach SDGs for healthy ecosystems

Describing such changes and proposing mitigation measures is a complex process, mainly because a lack of good data describing the situation before the hydropower regulation was undertaken but also since it is difficult to disentangle other factors influencing the riverscapes such as changes in climate and other anthropogenic impacts like agriculture, urbanisation, and road development.

Here we combine historic aerial imagery from the repository of the Norwegian mapping authority with a convolutional neural network to classify historic habitats in several rivers in Norway to establish pre-regulation conditions. Further, then the same methodology is used to classify imagery over the years after the regulation to make a database of riverscape development over time. The next step is to use GIS based algorithms to describe changes in habitat over time and to quantify the alteration. Data on climate development, anthropogenic factors and changes in floods and other flow regime components are then compiled and used to evaluate which factors drives changes in rivers. To better separate effects of regulation from other factors, we contrast the development in regulated rivers with unregulated rivers close by to properly attribute e.g., changes in vegetation to natural and regulation driven processes.

Results show reduction in point bars, infilling and loss of side channels and river braids and increased vegetation on previous open river bars. A consequence is narrowing of channels and shrinkage of open floodplains which is both an environmental issue and critical in flood conveyance.

Governance responses to tightening environmental requirements for hydropower – Finland, Germany and Sweden

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ABSTRACT: This article analyses how the existing governance systems are reacting, and how they prompt hydropower industry to react on tightening environmental requirements. Particularly, we analyse the incentives for small scale hydropower exits in Finland, Sweden and Germany.

Globally, hydropower provides 17% (4,250 TWh) of the total electricity generated. It is thus a key component of our economic wellbeing. Hydropower, and river damming for other purposes, however, block other economic activities that would depend on free-flowing rivers. These include fishing, white-water sports and other recreational activities. Some of the values hence generated are market-, some are nonmarket-based. Damming of rivers is also one of the main impediments of globally threatened freshwater ecosystems. Many of our economic activities depend directly or indirectly on ecosystem services provision of which depends on biodiversity. Biodiversity loss may thus weaken our economic wellbeing. In the long run, it also poses an existential threat to all human operations.

In addition to economic and ecological pressures, legal framework is of crucial importance for hydropower. The EU Water framework directive and the forthcoming Nature restoration law create pressure for hydropower facilities to undertake costly investments to reconcile hydropower generation with the ecological requirements. As with any industry, there are more and less profitable firms within the industry. In hydropower, profitability is generally worse for small facilities. Tightening requirements may render some of the facilities unprofitable in the long run.

How small facilities may react on increasing costs depends on the governance system. Basically, there are two alternative ways governance system can react on low, and worsening profitability: 1) subsidize small facilities to make them profitable or 2) generate mechanisms that assist them in quitting the operations and exiting the industry. The reaction may be passive: there might be an existing subsidy program that helps the least profitable, small facilities remain in business. There might also be additional subsidies to compensate for the costs of ecological mitigation measures such as fish passages. If such a governance structure, it will be easy to continue utilizing it. That is, it is plausible to expect that tightening regulations will be met with elevated subsidy levels. Germany offers an example of such a governance structure. There are subsidies for small scale hydro, with elevated payments if environmental measures are taken.

Finland and Sweden have governance structures that have a new inbuilt exit mechanism for small scale hydro. The incentives in Swedish program are designed by the industry, and in the Finnish program by government. We discuss the economic logic of these three governance systems, compare their information characteristics, and discuss their potential welfare implications.

Increasing biodiversity in heavily modified rivers without affecting production or balancing capacity of hydropower - examples of case studies

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ABSTRACT: About 45% of the Swedish electricity production comes from hydropower. Introducing more intermittent production as wind and solar in the system makes hydro more important for balancing of the electricity system. To fulfil demands connected to the Water Framework Directive a National Plan for the revision of the hydropower plant licenses have been decided. Most of Vattenfalls large-scale hydropower plants are situated in waterbodies that are classified as heavily modified. Therefore it is important to find measures that increase biodiversity without affecting production or balancing capacity.

Large-scale hydropower in Sweden have made major changes in rivers increasing more lake-like habitats and decreasing stream habitats. Connection to tributaries have been cut off. Species composition of benthic and fish fauna has been changed. The riparian zone in hydropower reservoirs is also affected. However it is still possible to improve biodiversity without affecting hydropower. Some examples of case studies are presented.

1) Restoration of connectivity between a tributary and the main river (Langas Lule river) – restoring spawning and nursing habitats for grayling and trout.

2) Site-specific restoration (Purkijaure Lule River) – Adaptation of an overflow dam. Creating new stream- and riparian habitats.

3) Create habitats adapted to regulated conditions (Juktån Ume River) - Change minimum flow pattern to imitate a more natural seasonal distribution to restore habitats for trout, graying and riparian vegetation.

Some new measures are also planned to test. For example to create habitats for stream living fish in outlet channels and artificial floating islands to create habitats for riparian vegetation and benthic fauna.

Hydropeaking and sustainable flexibility from hydropower

New approaches for a sustainable hydropeaking management: The HEM-Peak model and the role of channel evolution, river morphology and sediment dynamics

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ABSTRACT: Hydropeaking is one of the major hydropower-related disturbances of natural processes in river systems. The artificial flow fluctuations that are caused by the on-demand production of electricity are known for their severe impacts on aquatic ecosystems. These particularly affect those species and life stages that are not able to adjust their habitat selection to rapid up- and downramping rates. To date, the stranding risk has both experimentally and numerically mainly been investigated with variable hydropeaking graphs over stable river bathymetries. There is a lack of knowledge on how single, discrete peaking events vary concerning their impact on the stranding risk when the river morphology changes in the long-term and channel evolution perspective. The channel evolution is a crucial factor, which vary among European hydropeaking rivers but provides decisive boundaries for (i) possible adaption of aquatic species to the different hydraulic and sediment compositions (without hydropeaking) and (ii) mitigation measure design (with hydropeaking). The present study precisely addresses this knowledge gap by investigating (i) channel evolution processes and (ii) more in detail morphological changes on the reach scale over a period of 20 years and the related variability of the lateral ramping velocity as a proxy for stranding risk. For the latter, two alpine gravel bed rivers impacted by hydropeaking over decades were tested by applying a one-dimensional and two-dimensional unsteady modelling approach. Both the Bregenzerach River and the Inn River exhibit alternating gravel bars on the reach scale. The results of the morphological development, however, showed different developments in the period 1995–2005. The Bregenzerach River displayed continuous aggradation (uplift of river bed) over the various selected submonitoring periods. In contrast, the Inn River showed continuous incision (erosion of river bed). The stranding risk exhibited high variability on a single cross-sectional basis. However, on the reach scale, no significant changes in stranding risk were calculated for either river reach.

Moreover, another aim of the presented study is to introduce a new habitat modelling approach for (i) the assessment of hydropeaking impacts and (ii) for the design of hydropeaking mitigation measures based on the "hydraulic habitat stability analysis" (HHSA). The so called HEM-Peak model. Based on two-dimensional depth-averaged hydrodynamic-numerical modelling the HHSA is (i) applied, (ii) explained and (iii) discussed for several hydropeaking reaches in Austria, with hydro-morphological-diversity on the reach scale. The applied hydropeaking scenarios are related to seasonal variability in base flow and maximum discharge of the installed capacity of the different hydropower plants upstream.

Mitigating hydropeaking impacts and enhancing fish habitat by hydromorphological adaptions of the river bathymetry

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ABSTRACT: Dale power plant, located in Western Norway, was established in 1928. The outlet is approx. 2.8 km upstream the rivermouth in the Dale River. Salmon and sea trout live in the lower 4.8 km of the river. The power plant determines the flow of water downstream the outlet. The minimum flow here varies between 3 and 5 m^3/s and the powerplant has a maximum flow capacity of 44 m^3/s. Hydropeaking is applied during large parts of the year. The water flow from the outlet may therefore vary between 5 m^3/s and 44 m^3/s within 1-2 hours.

In today's energy system ability to balance the system is an important condition for security of supply and stability in the grid. With high shares of intermittent generation like wind power and solar PV the need for regulating power is increasing. This creates disadvantages linked to water level changes downstream of powerplants with outlets in rivers. In the Dale River, a rapid change in water flow can lead to the stranding of fry and fish. To compensate the disadvantages of rapid water level changes, some measures have been taken. Still, we see that this is might not sufficient.

To mitigate the environmental impacts of hydropeaking, both flow (direct measures) and habitat-related (indirect) measures have been implemented. The velocity of flow changes has been reduced by increasing the time intervals between turbine flow steps. Habitat adjustments were made in test sites to minimize dewatering areas, while maintaining high habitat quality.

In 2023 a new approach has been developed, wherein hydromorphological adaption of the river bathymetry has been applied to the entire river stretch downstream of the power plant. The design and the assessment of the mitigation was done based on detailed RTK-UAV measurements, 2D hydraulic modeling, habitat modeling, and the identification of natural river morphology types, which allowed to develop bathymetric adjustments that minimize the dewatering area and enhance habitat quality. For habitat modelling the novel HEM-Peak model was applied which enables (i) the quantification of hydraulic stable habitats in terms of base and peak flow and (ii) the quantification of the dewatering area as a proxy for the stranding risk. The main measures used were lowering and increasing of river sediment levels, restoration of diamictic plane bed reaches, restoration of side channels, spawning gravel augmentation, ripping of clogged sediments and ground sill removal. Impoundment of river stretches to minimize dewatering was completely avoided. The modelling results predict both beneficial aspects, the increase in hydraulic stable habitats and the decrease in the magnitude of the dewatering areas.

The presentation will describe the experience with the implemented mitigation measures and introduce the concept of adjusting the entire river's bathymetry based on natural river morphology types, minimizing dewatering areas and enhancing habitat quality.

The benefits of artificial refuges as hideouts to pulsed flows for Iberian cyprinids

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ABSTRACT: The impacts of hydropeaking on fish communities are widely recognized, yet it is challenging to identify a causal pathway between artificial induced-flow variability and a measurable fish response. Moreover, in the context of widespread biological invasions, there is limited knowledge of how invasive species interact with native species, particularly during pulsed flows, and on the application of mitigation measures to reduce the impacts of pulsed flows associated with hydropower production, particularly for cyprinids. The objective of this work was to examine the effectiveness of artificial refuges as hideouts to alleviate the impacts of pulsed flows on the Iberian barbel (*Luciobarbus bocagei*). In addition, we evaluated whether the presence of the invasive bleak (*Alburnus alburnus*) affected the use of artificial refuges by I. barbel. The study was conducted at an indoor flume where we installed artificial refuges constructed in maritime plywood, conferring overhead cover and low-velocity areas. In the first experiment, we tested two structures differing in the angle of insertion with the flume wall (i.e. 45º and 70º). The best structure was selected to test the effect of bleak on its use by I. barbel. Fish were exposed to a base-flow (7 $L.s^{-1}$) and a peak-flow (60 $L.s^{-1}$) event. We registered the frequency and time of use of the structure by fish. In addition, the levels of glucose and lactate were quantified to investigate if the created hydraulic conditions and the presence of bleak would set off physiological adjustments. Preliminary results indicate that the 45º structure was the most effectively used and resulted in the highest permanence time, in comparison to the 70º. The presence of bleak hindered the ability of I. barbel to use the available structure, in opposition to the highest frequency of use by I. barbel without bleak, particularly during peak flows. In addition, the levels of glucose and lactate were significantly higher for I. barbel in the presence of bleak and in the peak-flow event in comparison with the base-flow event where only native species were present. Finally, the 45º refuge was upscaled and implemented downstream of two hydropower plants and equipped with underwater motion detection cameras. With this monitoring system, we expect to find fish use patterns before, during and after hydropeaking, and to identify seasonal behavioural variations. This study provides novel findings on the efficiency of insertion angles to attract fish to a refuge and on the interactions of native with invasive species in highly fluctuating flow environments, bringing additional awareness to the importance to manage artificial flow variability and biological invasions to prevent freshwater biodiversity loss.

The influence of repeated hydropeaking events on early live stages of European grayling (*Thymallus thymallus*) and common nase (*Chondrostoma nasus*)

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ABSTRACT: Short-term water releases from hydropower plants, called hydropeaking, negatively affect river biota, such as fish. Much is already known about the responsible factors characterizing the ecological consequences. The current understanding of the ecological effects of ramping rates, time of day, or seasonality on fish stranding and drift is mainly based on research on single hydropeaks. There is a need to understand how peaking frequency affects fish drift and stranding risk in the longer term, subsequently, the population. Experimental studies can aid to fill this knowledge gap on multipeaking effects, constituting a profound basis for the improvement of mitigation measures.

This study investigated how recurring hydropeaking events during day and night affect the drift and stranding of young-of-the-year European grayling (*Thymallus thymallus*) and common nase (*Chondrostoma nasus*) in a semi-natural outdoor channel. Grayling multi-peaking experiments consisted of nine peak events within 24 hours, whereby the first three occurred during the day, the next three during the night, and the last three during the next day. Nase experiments consisted of five peak events, each starting 15 minutes after the preceding one; this series was conducted both during the day and night.

Our data show that drifting and stranding rates of nase were highest at the first hydropeak; the following 2-4 peaks showed reduced responses. This pattern was the same for day and night experiments. The results of grayling showed that drift was reduced after the first event, particularly the nighttime peak events exhibited lower drift and stranding rates compared to the data from single-peak experiments, indicating a behavioral change due to experience gained during previous peak events a few hours before. Fish drift and stranding were low for all peak events during three events on the second day.

To gain more information on this behavioral phenomenon, we tested two groups of juvenile grayling during another multi-peaking experiment, splitting fish into two groups. The first group consisted of individuals which neither drifted nor stranded during experimental hydropeaking events 24-48 hours prior to the start of this multipeak setup. The second group comprised individuals which had no hydropeaking experience during the previous few days. Group comparisons showed no clear difference in drift or stranding rates, except for stranding during the first nocturnal peak event, suggesting that most of the experience acquired by fish from the first group gained 24-48 hours prior seemed to have vanished.

The findings of this study show that extrapolating results from single peak experiments to frequent hydropeaking schemes may, under certain conditions, overestimate the cumulative drift and stranding rates of young-of-the-year fish. Our data suggest that reducing hydropeaking intensity is particularly important after a pause phase. We suggest that the notion of releasing a small 'warning peak' to prevent extensive drift and stranding should be investigated in future studies. Overall, this study contributes key knowledge regarding hydropeaking impacts and mitigation.

Hydropeaking effects on two cyprinid fish species, barbel and nase, under experimental conditions emphasizing larval stranding

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ABSTRACT: Hydropeaking, characterized by fluctuating river flows, is considered one of the most significant impacts on riverine biota downstream of hydropower plants. Many studies have, therefore, investigated how various taxa are affected by artificial flow fluctuations. However, cyprinid fish received little attention in hydropeaking studies so far, and extensive knowledge gaps remain of this highly diverse fish family. Therefore, we aim to assess the effects of artificial flow reductions on two European cyprinid indicator species, the common barbel (*Barbus barbus* L.) and the common nase (*Chondrostoma nasus* L.).

We conducted mesocosm experiments (2.25×2 m) under semi-natural conditions with early developmental stages (body length <2 cm) at an outdoor research facility (http://hydropeaking.boku.ac.at), simulating different hydropeaking scenarios with varying down-ramping rates during daylight conditions and at night time. At each trial, we stocked 100 individuals from one species at peak flow (80 $L.s^{-1}$). After 15 min. of acclimation, the flow rate was automatically lowered to constant low flow conditions (10 $L.s^{-1}$) with variable ramping rates , ranging from 0.3 to 3.0 $cm.min^{-1}$. As a response parameter, we quantified larvae stranded on the flat and gently sloped bank mimicking typical riparian habitats preferred by cyprinids.

Our results show distinct diurnal patterns for both species, with higher stranding rates at night than during the day for all experimental scenarios. Additionally, the data reveal differences among the tested down-ramping rates and indicate interactions between these ramping rates and the time of day. Differences in stranding between nase and barbel may be associated with differences in the water temperature – related to their inherently different timing of emergence from the sediments in late spring and early summer, respectively – and ecological factors. The study outcomes will benefit the discussions on species-specific mitigation actions by providing evidence on the effects of rapid flow down-ramping on early cyprinid stages.

Sustaining hydropower production and salmonid populations: Ecological models for assessing hydropeaking and habitat restoration scenarios

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ABSTRACT: Hydropower is an important source of clean and renewable energy, but damming rivers has also caused severe losses of freshwater biodiversity. Thus, there is a great need for new ecological modelling tools to protect freshwater biodiversity while continuing to provide streamflows that can produce clean energy. In this project, we developed an individual-based model (IBM) to understand the effects of hydropeaking on fish populations. We parameterized and applied inSTREAM (7.2-SD) for high-conservation value populations of endemic brown trout (Salmo trutta) and Atlantic salmon (Salmo salar) in River Gullspång, a key hydropower-producing river in Sweden, under various flow scenarios. We calibrated the model by comparing predicted versus observed growth of juvenile fish under the current hydropeaking regime. We then modelled growth, survival and distribution under flow scenarios with and without hydropeaking. We observed that hydropeaking generally produced modest negative effects on growth and survival of both species; survival was more affected than was growth; smaller fish were more affected than larger fish. Under hydropeaking, on-peak (high) flows provided less profitable feeding conditions (less growth) and modelled fish were subject to more predation (lower survival). Our model appears to capture ecologically-relevant behavioural patterns under hydropeaking, for example, habitat selection and activity (feeding vs. hiding) in response to rapid flow changes. Collecting robust field data for such multiple management scenarios, even if possible, would be time-consuming and costly. Our study demonstrates the potential of IBMs as powerful tools for testing research questions and assessing and prioritizing alternative management strategies in regulated rivers.

Keywords: growth, hydropeaking, individual-based modelling, salmonid, survival

Unravelling the complex relationship between artificial flow fluctuations and cyprinid fish: a comprehensive analysis

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ABSTRACT: The anticipated increase in renewable energy usage to reduce reliance on fuel-based sources will add further strain to riverine ecosystems. As wind and solar energy production fluctuates, hydropower, particularly storage hydropower, will play a more significant role in maintaining grid stability. However, such operations introduce unnatural sub-daily flow fluctuations that can have negative ecological impacts on fish, including drift and stranding. The effects of these fluctuations, known as hydropeaking, have been studied extensively in relation to salmonid fish, while cyprinid fish have received little attention in this area of research.

Our work seeks to address gaps in our understanding of the impact of sub-daily flow fluctuations on cyprinid fish. We aim to achieve this through two approaches. Firstly, by leveraging a vast database to model the effects of hydropeaking on selected cyprinid species on the national level of Austria. Secondly, by conducting hydropeaking experiments using unique nature-like channels that specifically focus on early cyprinid life stages. By operating on both a macro and meso level, the project adopts an integrative approach.

Here, we synthesize results from database assessments and various experimental setups to gain a comprehensive understanding of the impact of (a) hydro-morphological stressors and (b) hydropeaking flow data on fish populations. The database assessments provide insights into the population status, considering hydro-morphological stressor groups and hydropeaking flow data combined with other relevant stressor data. The mesocosm and flume experiments quantify stranding in response to (a) down-ramping rate, (b) daytime, (c) river bank slope, (d) bar morphology, (e) fish species, and (f) fish size/developmental stage.

The results have significant relevance due to the broad distribution of cyprinid fish. They could help establish mitigation strategies in river systems facing hydrological stress, thereby improving ecological integrity in rivers worldwide.

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Connectivity, barrier and solutions

An overview over upstream fish passages past barriers in Norway

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ABSTRACT: The presentation provides an overview of the 2020 status of fish passages over barriers in Norway, using data from Miljødirektoratet's database. We examine the quality of the data and compare it with physical measurements in selected passages, focusing on their functionality, target species, and selectivity for species or size classes. In addition, we assess safe downstream passage where information is available.

The results reveal that most passages were built for salmon, even in water bodies where other species are abundant. Furthermore, a large percentage has reached the end of its lifespan and requires significant rehabilitation to ensure fish migration in Norwegian waterways in the future.

Furthermore, we demonstrate that fish passages can be evaluated quickly based on simple parameters. Finally, we present the latest fish passes constructed according to best practice guidelines for upstream and downstream migration. We focus on their performance, initial experiences during construction, and their effects on fish migration, as far as they are monitored.

Impact of weirs and hydropower regulation on brown trout, invertebrates and people in an inland river; expanding the concept of environmental design

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ABSTRACT: In this study we investigate the impact of weirs on the local brown trout population and benthic invertebrates in a regulated inland river using the principles of environmental design, originally developed for regulated salmon rivers. The investigated stretch of river Nea, is approximately 33 km and is characterized by 32 weirs. The hydrological analyses show that the water flow is significantly reduced after regulation, both during summer and winter. Historically, River Nea has been an important spawning and recruitment river for the large brown population in Lake Selbusjøen. However, because of the large number of weirs and reduced waterflow the status for the brown trout and the ecosystem has been questioned

We studied how the numerous weirs in the river impact the local brown trout population and benthic invertebrates and have identified bottlenecks for the population. Using both traditional methods and modern tools such as remote sensing drones, green lidar, as well as genetic methods such as environmental DNA and barcoding to accomplish this. The leisure use of River Nea and nearby areas by local inhabitants and tourists has been studied, as well as how potential mitigation measures are perceived. Our results show that the spawning stock of the brown trout population is very small, inbread and fragmented probably due to migration barriers in the form of weirs that limit the migration and gene flow within the population. The benthic invertebrate biodiversity in total is reduced, compared to what we expect and number of species is reduced in weir pools, compared to rapids. Surveys show that River Nea is of great importance to locals and tourists and that weirs are important for peoples perception of the landscape. However, people are positive to measures that improves the environmental conditions for brown trout and invertebrates.

The bottlenecks for the brown trout population and invertebrates in the investigated stretch are linked to both hydrological and habitat-related conditions. The weirs have been identified as a strong bottleneck and to mitigate this challenge we have suggest some mitigation measures and modification of the weirs. We suggest to modify design of weirs to re-establish connectivity, such as migration routes for spawning salmon, re-establish un-used spawning areas and maintain deeper areas for overwintering. As a main measure to achieve these requirements, we propose that the weirs be partially opened by means of ramps with migration channels.

Behaviour of post-spawned Atlantic salmon (*Salmo salar*) migrating past a hydropower dam.

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ABSTRACT: As the climate crisis unfolds, renewable energy production is becoming increasingly important in the ongoing effort to transition from fossil fuel-based economies to green economies. Hydropower production, one such form of renewable energy production, represents an important industry, but can have negative consequences on ecological communities, and particularly migratory river species. One such species, the Atlantic salmon, *Salmo salar* (hereafter 'salmon'), is negatively affected by hydropower production during its up- and downstream migrations. Dams can impede, hinder, or delay salmon migration. Migration delays can result in lowered fitness, while swimming through turbines can result in injury or mortality. Some life stages of salmon are relatively well-studied, such as the downstream migrating juvenile fish and upstream migrating adults. However, very little is known about the downstream migrating post-spawner adults (hereafter 'kelts'), an important salmon life stage with high conservation value. Particularly, baseline knowledge about how kelts interact with different hydraulic conditions, which is crucial for developing cost-efficient and safe methods to help kelts bypass dams and reduce migratory delays, is limited. Thus, the aim of this work is to gather baseline information about how salmon kelts interact with different hydraulic conditions present at a hydropower dam. To do so, tracking data was collected from forty-eight kelts in the River Orkla, Norway, upstream of the dam at the Svorkmo hydropower plant. This tracking data was coupled with hydraulic data simulated using computational fluid dynamics model (OpenFOAM). We first assessed the passage efficiency of the kelts at the dam. Next, we assessed various characteristics of kelt swimming behaviour, including swimming depth preferences and swimming speeds. These results are a first evaluation of kelt swimming behaviour directly related to the hydraulic conditions present upstream of a hydropower plant. Thus, they should be insightful to those interested in the interaction between hydraulics and fish behaviour, as well as those interested in downstream passage solutions and river management.

A framework to identify cost-effective mitigation measures using Influence Diagrams

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ABSTRACT: Hydropower's impacts on the aquatic ecosystem and the benefits that hydropower generates as a renewable energy source have been and are widely investigated. However, how to find the most cost-effective mitigation measures to maintain a sustainable fish population while maintaining or maximizing the benefits of hydropower production is still a challenge. This challenge is partly triggered by the uncertainties related to the lack of data, difficulties related to finding one or more indicators to measure effectiveness, and the transferability of data from different case studies to a more general context. To deal with these challenges and as part of the EU-funded research project FIThydro (Grant Agreement number 727830, duration 2016-2021), we have been working in a framework that uses Influence Diagrams as probabilistic networks for identifying cost-effective mitigation measures (both stand-alone and in combination) based on their likelihood of success and their costs. This framework has been applied in three different test-cases: Las Rives in France, Anundsjö in Sweden, and Guma/Valdecondes in Spain. Each case had different challenges and mitigation measures. The development of the framework for each site and the results shows that it can be used to provide an initial guideline for water managers and stakeholders, identify potential knowledge gaps, trigger discussions, and offer first indications on where efforts should be placed to find potential mitigation measures. The method has been furtherly disseminated and promoted in a follow-up project, the FITHydro FORSTERK project (RCN 333224), focusing on the Scandinavian context.

Bidirectional use of a natural fishpass

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ABSTRACT: Fishways are built worldwide to restore longitudinal connectivity in rivers. According to current doctrine they are only suitable for upstream migration and they are thus not considered viable for downstream migration. Some recent studies contradict this general assumption and demonstrate the potential of fishways for bidirectional movement.

Our study extends the understanding of the potential of fishways for bidirectional movement by investigating their efficiency at a run-of-river hydro power facility at the Danube River.

We tagged fish in the tailwater and in the impoundment of the HPP Ottensheim-Wilhering using PIT tags (Passive Integrated Transponder). PIT Antennas mounted in the fishway of the HPP permanently detect the previously tagged fish and make it possible to estimate the use of the fishway for up- and downstream movement.

The investigations contradict the general assumption that fishways are only suitable for upstream migration and show that fishways are used bidirectionally by potamodromous species. The paradigm that fishways are not appropriate for downstream fish passage or have no role in quantitative terms, needs to be reconsidered.

Passage Efficiency of Downstream Moving Fish at a Bypass Gate with Bottom and Top Opening

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ABSTRACT: Fish guidance racks (FGRs) with adjacent bypass systems (BSs) are effective solutions for safe downstream passage at different types of HPPs and water intakes for many fish species. The function of a BS is to effectively attract and safely transport fish to the downstream reach of the river. Various field and laboratory studies indicate that a gradual velocity increase into the bypass leads to enhanced acceptance. To reduce electricity generation loss and control the bypass discharge, a vertical axis flap gate with local openings has been in use at the bypass inlets of many FGR-BSs. However, such gates create high velocity gradients and absolute flow velocities that may affect the movement behavior of approaching fish.

To investigate fish acceptance at local bypass inlet openings, live-fish tests with brown trout (*Salmo trutta*) and barbel (*Barbus barbus*) were conducted in a 30 m long and 1.5 m wide ethohydraulic flume at the Laboratory of Hydraulics, Hydrology and Glaciology (VAW) of ETH Zurich. The physical model featured part of a FGR with foil-shaped vertical curved bars (f-CBR) with a horizontal approach flow angle of 30° and a clear bar spacing of 50 mm. At the downstream end of the FGR, a bypass inlet gate (W x H = 0.7 x 0.9 m) with a bottom (W x H = 0.18 x 0.25 m) or top opening (W x H = 0.18 x 0.3 m) was installed. The spacings between bars at the upstream side of the FGR were covered with a net to ensure 100% fish guidance to the bypass, given that the experimental design was focused on determining the efficiency of the bypass design for fish acceptance and passage. The experiments were conducted at three different discharges and resulting approach flow velocities. Flow fields were mapped by measuring three velocity components with an acoustic Doppler velocimeter (ADV) probe in a densely spaced measurement grid. Fish behavior and movement was obtained by visual observation and video camera recordings.

The two fish species often showed an avoidance behavior to high velocity gradients around the bypass opening. Barbel showed greater sensitivity to high velocity gradients compared to brown trout. Bypass passage efficiency (BPE) of the top opening was less than or equal to 21% for both species and all approach flow velocities. BPE of the bottom opening was significantly higher than for the top opening. The results illustrate that bypass inlet gates with local openings to regulate discharge can affect bypass acceptance and thus fish guidance efficiency of the overall FGR-BS. Hence, a thorough design of the bypass inlet is crucial for an environmentally sustainable and economic operation of HPPs in the future. The present contribution will give an overview on the current bypass designs, present the hydraulic and live-fish results of the laboratory tests, and give an outlook on the future investigation of effective bypass designs.

Bubble curtain and novel ‘dancing rods’ behavioural guidance solutions for out-migrating European eels and Atlantic salmon smolts

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ABSTRACT: Hydropower plants and their adjacent infrastructure obstruct migratory pathways, and the lack of free-flowing rivers worldwide is a significant factor contributing to the rapid decline in migratory fish populations. To ensure river connectivity, restoration of downstream migration is necessary in addition to upstream. During downstream migration, fish rely on bulk water flow and require a guidance system to steer them away from dam intake channels and towards safe fish passage. While some physical guidance structures have been effective, they are expensive to maintain and difficult to scale up for large hydropower plants. Alternatively, guidance systems based on fish behaviour may provide an alternative, but finding a viable solution has been challenging. We conducted experiments using a bubble curtain for the endangered European eel and a novel "dancing rods" behavioural barrier for Atlantic salmon smolts in a large experimental flume and compared them to no-barrier control. Our findings showed that the bubble curtain was ineffective for guiding eels, as the guidance efficiency was similar to the control treatment. In contrast, the "dancing rods" had significantly higher guidance efficiency compared to the control treatment. Based on our results, we conclude that the bubble curtain is not practical for eel guidance, while the "dancing rods" principle could be applied to the design of future behavioural guidance solutions. Discovering effective behavioural guidance solutions that companies can implement is crucial for ensuring downstream fish passage and restoration of river connectivity.

International hydropower, sustainability and the use of LCA

Mass fish mortality events: a (novel?) threat to hydropower in tropical systems

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ABSTRACT: Fish mortality events at hydropower plants are a known phenomenon and can be associated with various mechanisms including water quality and flow alterations downstream of the dam and fish interaction with structures such as turbines and/or spillways. In the Neotropical region, a recent study demonstrated that mass mortality events are likely more common at hydropower plants than hitherto thought, posing questions about the extent of knowledge to understand the mechanisms leading to such events and the ability to provide informed management decisions to mitigate the problem and avoid future problems by modifying infrastructure design.

To shed light in this scenario, this study builds up on a unique case from Sinop Dam located at the Teles Pires River, Central-West region in Brazil. Sinop Dam started operation in the Teles Pires River in February 2019 with reservoir filling. During that process, the spillways were opened to ensure downstream flows and fish kills started to occur immediately downstream, with several mortality events registered in almost a daily basis for several months, and with other sporadic events occurring over a 18 month period (February 2019 to August 2020). Given the magnitude of the fish kills, an expert panel was assembled to investigate the mortality events: both their causes and potential mitigation solutions. This study aimed to identify the main factors likely associated with mortality, quantify the biomass as well as the diversity of fish groups and species affected.

In total, tonnes of fish died downstream of Sinop Dam during the study period affecting 87 species. The period with the highest mortality affected 43% of the total biomass of dead fish collected and over 65 species, whereas the lowest mortality involved 6% of the total dead biomass and 27 species. Statistical modelling using the General Linear Mixed-Effects Models (GLMM) approach showed that most of the mortality events were linked to a rapid increase in spillway discharge, promoting gas supersaturation above lethal thresholds for fish. Also, at specific conditions the interaction of fish with the turbines were deemed to be the cause of mortality, likely because of fish entrainment into the draft tubes during operation with the downstream stop log.

These results contributed to the identification of management solutions to mitigate fish mortality at Sinop Dam, particularly with recommendations to spillway operation and design modifications. Following spillway operation modifications, no further mass mortality events have been recorded. However, such operational measures are constraining, and design modifications are being studied. As a result, an ambitious ecological and technical research program on supersaturation effects on neotropical fish and spillway design is currently underway.

Uncertainty and complexity in ecological and social mitigation of hydropower in developing countries

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ABSTRACT: Hydropower project development is increasing in developing countries and poses potential threats to eco-sociological systems if they are not sufficiently planned and mitigated. Despite the widely recognized importance of basin-wide energy development plans to adequately protect biodiversity and local communities (including indigenous communities), high-level energy planning to determine the best type and place for situating energy production projects (including hydropower) remain rare, which places the burden on potential developers to identify ecological and social feasibility. In developing countries this is often compounded by a context of high levels of uncertainty resulting from a general lack of information on species distribution and ecology in many regions, which can often hamper the transferability of evaluation and mitigation tools developed in Europe or North America to these areas (for example, microhabitat simulations, detailed hydropeaking impact assessments for target species, etc). Finally, the implementation of ecological mitigation is even more contingent on social aspects in developing countries than elsewhere, as most mitigation measures and offsets require integration of changes in livelihood practices (high dependence on ecosystem services) and overall social adherence, particularly in areas outside of direct project control, which are often subject to cumulative impacts. This last challenge can also be an opportunity for the project to contribute to the implementation of more sustainable practices (for example, in resource extraction) over an extended spatial area.

Drawing upon examples from several projects in developing countries from three continents and at different stages (in development, construction or operation), some solutions to the specific challenges that hydropower development poses in the developing country context (particularly tropical ecosystems) will be illustrated, as well as the unresolved issues and perspectives on how to address them. Examples of good practice from these projects include benchmarking potential projects in the pre-development phase (tools and criteria), developing local capacity for environmental monitoring over the long-term and community-based fisheries and forest management, conducting holistic environmental flows assessments and eco-social feasibility assessments for river-based offset programs including perspectives on how developing governance structures and community-based conservation (multi-use forests for example) can potentially contribute to mitigation goals, particularly of non-Project lands that are not legally protected. In particular, the lack of ecological information has been addressed by anticipating long-term research programs (on fish distribution, ecology, taxonomy and migration patterns), which associate local expertise with international experts to also increase local capacity in the long-term (notably for eDNA and genetic analysis).

Analysis of flow variation in the Kelani River due to the impact of the Laxapana Hydropower System in Sri Lanka

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ABSTRACT: The electric power generation of Sri Lanka is mainly based on three primary energy sources such as thermal, hydropower and other renewable sources. Hydropower generation represented 31% share of the total installed capacity of the national grid (CEB, 2021). Laxapana is one of the major hydropower complex in which New Laxapana generates a total hydropower capacity of 100MW and it is situated in the upper part of the Kelani River basin. The lower part of the river basin is topographically flat. So, major flow changes are observed in the upper region of the Kelani basin. Power regulations argue to have streamflow variations in the upper Kelani basin. Therefore, it is vital to analyse flow variations of the river due to this major hydropower scheme by developing a hydrological model and evaluating the flow changes during the respective months and years, comparing with and without hydropower scenarios.

Hidden effects of water impoundment on surrounding vegetation and water consumption

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Evapotranspiration is the water flux from the Earth's surface to the atmosphere. Calculating changes in evapotranspiration in time can also serve as a proxy of the human impact on the water cycle; they also represent human water consumption when driven by anthropogenic activities. Evapotranspiration changes can be used to assess the sustainability of human water consumption. For instance, a global analysis of changes in evapotranspiration has shown that current human water consumption may have already exceeded a safe operating space for humankind due to unaccounted evapotranspiration from reservoirs and irrigation. Two hypotheses exist to explain this finding. First, the hydroclimatic effects of water impoundment may be responsible for increasing evapotranspiration beyond the surface of the water-impounded reservoirs. For instance, we calculated changes in evapotranspiration and water consumption from a reservoir in China to find that the reservoir had increased evapotranspiration, explained only by the additional effects of the reservoir that extend beyond the water surface. To determine if vegetation changes related to the reservoir impoundment were the reason for increasing evapotranspiration, we further developed a dendrochronological study, measuring the growth of trees around the reservoir. Surprisingly, we found that tree growth after impoundment could only be explained by a simultaneous effect of favourable regional climate conditions and the reservoir's impoundment. Nevertheless, this effect appears to depend on the reservoir's location and hydroclimatology, as a reservoir in a more humid region in Colombia does not show this effect. The second hypothesis is that the increase in evapotranspiration is an artefact of changes in water storage due to impoundment, as water from the reservoir may infiltrate the surroundings and be accounted erroneously as water losses to the atmosphere. We used Interferometric Synthetic Aperture Radar (InSAR) to detect any potential ground uplift or subsidence surrounding Lake Mead in Nevada, United States, and verify this effect. Although we did not find evidence of this effect, we noticed that the ground surrounding the reservoir subsided or uplifted following the changes in the water load within the reservoir. Such deformation can also become a proxy of water changes in the reservoir and its surroundings. Our accumulated results show that water regulation for agriculture or hydropower may be an important component of water change in the Earth system.

Biodiversity footprint of hydropower: introducing aquatic pressures into the Product Biodiversity Footprint (PBF)

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ABSTRACT: Hydropower is a renewable energy whose interest lies in its flexibility and its low carbon footprint compared to other energy sources. However, hydropower generates impacts on biodiversity. These impacts are generally assessed through a "Pressure - State - Response" model, which allows for quantifying local impacts on biodiversity and related mitigation measures, focused on the direct and indirect impacts of the works and the operation of the facilities.

In order to go further and reduce its impact on the entire value chain, EDF is developing an eco-design process based on the principles of Life Cycle Assessment (LCA) approach. The objectives are to reduce the environmental footprint of its facilities by re-examining the organization of worksites or the electricity production as well as the techniques and processes used to manufacture materials (concrete, for example) and equipment. The main indicators considered are climate, natural resources and land use change.

However, this approach does not consider aquatic biodiversity and therefore remains insufficient to assess the biodiversity footprint of hydropower. One of the methods under development is the Product Biodiversity Footprint (PBF), proposed by I-Care and Consult and Sayari, and its related Site Biodiversity Footprint (SBF). PBF and SBF are able to consider local impacts on biodiversity using a LCA-based approach. However, so far, PBF and SBF only focussed on terrestrial biodiversity.

To include biodiversity impacts in its eco-design approach, EDF decided to collaborate with I-Care to adapt the PBF (Product Biodiversity Footprint) to hydropower specifications.

First, the specific pressures of hydropower dams and plants on aquatic and terrestrial biodiversity were identified and assigned to the 5 major pressures of the IPBES (land use change, direct exploitation, climate change, pollution, invasive alien species). Based on a literature review, methods compatible with LCA were identified that allow quantifying pressures currently missing in the PBF, i.e. down- vs upstream temperature change, water stress and degradation of riparian zones. Finally, a semi-quantitative approach is under development and tested to characterize the

remaining pressures for which no LCA models exist yet, i.e. fragmentation, flow alteration, invasive aquatic alien species, and riparian area dewatering.

The communication will present the different steps in the development of the method as well as the data required for its use. The benefits and limits of the approach, as well as the implementation challenges will be discussed.

Changing Perspectives: a new macroinvertebrate community metric to evaluate habitat loss in residual flow stretches

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ABSTRACT: In Austria, hydropower is one of the most important sources of renewable energy, providing more than half of the country's energy supply. Despite creating baseload energy, one of its main strengths is balancing fluctuations in energy production and demand. Therefore, large reservoirs are created in high alpine regions by abstracting water from multiple streams, which is then pumped or drained into storage lakes to gain the necessary capacity and flexibility for energy production. Abstracting water can nevertheless have severe impacts on the ecosystem, by altering environmental conditions like habitat availability and quality. To fulfill the requirements of the EU's Water Framework Directive hydrologically and morphologically altered water bodies need to be assessed according to the resident communities of aquatic organisms to analyze their ecological status and subsequently either maintain or improve the ecological status.

A wide range of metrics and metric combinations is available for assessing macroinvertebrate communities to evaluate the ecological status based on this organism group. Nevertheless, all of these metrics depict the investigated stretch as a kind of "decoupled system", without considering the size of the whole water body in relation to the unimpacted stretch. While this approach is perfectly suitable, if the studied impact is supposed to be viewed as independent of the size of river cross-section (e.g. in case of altered flow velocity, or pollution), it neglects one of the main effects of water abstraction on riverine ecosystems: the loss of wetted area and the concomitant quantity of available habitats.

In the present study, six high alpine streams were investigated, all of which are affected by water abstraction. At each stream one sampling site was situated above the water abstracting weir as a reference site and three downstream, in the residual flow stretch. At each sampling site macroinvertebrate communities were analyzed. The stream width was measured and a representative median value was calculated per site. Based on the gathered data, metrics considering the abundance/biomass per area can be complemented by one dimension (multiplication with stream width), offering a possibility to depict the total abundance and biomass of a river section. The use of this new metric offers an opportunity to evaluate residual flow stretches from another perspective. In combination with other, well-established macroinvertebrate metrics it can create a basis for a holistic evaluation system as well as for implementing adequate mitigation measures to reduce the impact of water abstraction on the ecosystem.

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Hydropeaking, flexibility and impacts downstream HP outlets

The ecological effects of sub-daily flow variability on riverine fishes – a systematic review

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ABSTRACT: The contribution of renewable energy to the global energy portfolio is increasing. The flexibility of hydropower to support increased integration of intermittent renewable energy production such as solar and wind makes it an attractive option for power producers responding to grid demands for electricity on a short timescale. Operating hydropower dams to respond to real-time energy market conditions can result in rapid and abnormal fluctuations in downstream flow, called hydropeaking. Hydropeaking alters the timing, magnitude, and rate of change of natural flow regimes by decoupling seasonal climate and flow patterns and rapidly changing river discharge via pulses of water from upstream reservoirs. Consequently, hydropeaking can affect wetted width, temperature, habitat quality and availability, and other biotic and abiotic river characteristics downstream of hydropower facilities. In this systematic review, we summarize and synthesize the growing body of literature on the ecological effects of sub-daily flow variability on riverine fishes associated with hydroelectric power production. Specifically, we characterize the magnitude and direction of the suite of reported impacts of hydropeaking on fish and the techniques and metrics used to assess these impacts. We also identify research opportunities to address knowledge gaps and explore emergent dynamics. Findings from this review will help illuminate the generality of hydropeaking impacts on fish and inform hydropower operation strategies that balance flexible hydropower production with downstream ecosystem integrity.

Effects of spatio-temporal variability of hydropeaking on juvenile fish

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ABSTRACT: Storage hydropower plants buffer volatile energy production by renewable energy sources. Generating energy flexibly, however, causes artificial flood waves (hydropeaking), which can negatively affect the river ecosystem. Fish are among the groups of organisms most affected by hydropeaking. The early life stages of fish are particularly endangered by rapidly changing water levels as they have lower swimming abilities than more mature fish. Also, their preference for near-bank habitats puts them at increased risk. In the up-ramping phase of a hydropeaking wave, fish may be displaced downstream and laterally, while in the drawdown phase, riverbank dewatering may cause stranding and trapping on previously wetted areas. Therefore, research has aimed to understand hydro-ecological relationships related to hydropeaking wave criteria (e.g., ramping rate, amplitude) and identify flow thresholds. However, most studies are either experimental or, if involving fieldwork, only consider single rivers and selected species (e.g. brown trout, grayling, rheophilic cyprinids). Here, we conducted a field study integrating multiple rivers and species, considering a longitudinal gradient for each river. This work integrates various hydrological aspects, aiming to better understand the ecological effects of hydropeaking frequency. A hydropeaking event is defined as exceeding a threshold related to the intensity of natural flow fluctuations under consideration of the respective river size used as a benchmark. This enables a standardized hydrological monitoring, which can then be linked to ecological measurements. In order to take legacy effects into account, hydrological conditions before sampling related to distinct life cycle periods (spawning, incubation, larval and juvenile stage) are included to allow identification of the most critical periods for fish. A better understanding of the impacts of hydropeaking can be gained by looking at the critical hydrological thresholds and the most influential periods/life stages. This also results in implications for mitigation measures and the operation of hydropower plants.

The effects of supersaturation on benthic invertebrates in two Norwegian rivers

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ABSTRACT: Gas supersaturation occurs when the total dissolved gases (TDG) in a body of water exceeds what is possible to dissolve given the current temperature and pressure. The TDG of natural rivers hovers around 100% and can reach supersaturated levels up to 110% TDG for short periods in waterfalls, during rapid temperature heating, and during periods of intensive photosynthesis. Hydropower production can create prolonged periods of supersaturation above 110% TDG and can cause spikes in saturation reaching over 200% TDG. Aquatic organisms exposed to supersaturation above 110% TDG can develop gas bubble trauma causing lethal and sublethal effects on the organism.

We have for the first time investigated how abundance, diversity, and community composition of benthic invertebrates are affected by gas supersaturation in field settings. We sampled benthic invertebrates in unaffected habitats upstream and affected habitats downstream of the power plants Skibotn and Brokke hydropower plants, which are known to produce supersaturation in the rivers Skibotnelva and Otra, respectively. In the year before sampling 123 days with a TDG above 110% were recorded in Otra compared to 32 above 110% TDG in Skibotnelva.

Environmental variables were measured at each site, invertebrates were sorted and identified to species in the lab, and the dry mass of each sample was weighed. The results indicate that the density, diversity, and dry mass of benthic invertebrates were significantly lower in habitats affected by supersaturation in Otra, whereas the density was significantly lower and diversity was significantly higher in affected habitats in Skibotnelva. Most taxa were absent or had drastic decreases in density at affected sites in Otra compared to unaffected sites. These differences were likely due to longer periods of supersaturation at high levels in Otra compared to Skibotnelva. Benthic invertebrates perform ecosystem functions that are crucial to stream integrity. Changes in diversity, biological production and community structure caused by gas supersaturation are therefore likely to reduce the resilience of the ecosystems and affect the whole ecosystem.

The effects of gas supersaturation on fish and benthic invertebrates

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ABSTRACT: Freshwaters are rarely saturated with more than 100% air. Gas supersaturation can still occur in natural settings, and especially downstream from waterfalls. In hydropower plants, supersaturation can occur when air in entrained in the tunnel system and saturated in water under high pressure. Exposure to supersaturation negatively affects aquatic biota through the formation of bubbles in the tissue, analogous to the bends in humans. We have performed lab experiments with up to 120% saturation to find the tolerance towards supersaturation in Atlantic salmon parr-, fry- and alevins, brown trout, minnow, rainbow trout, and nine species of common benthic invertebrates. We have also tested in -situ effects on Atlantic salmon and brown trout in the River Otra.

Clinical signs of gas bubble disease in fish start to develop at 105% saturation, subacute mortality occurs from 110% saturation, and acute mortality occurs from 115% saturation. Parr of Atlantic salmon and brown trout are most sensitive towards supersaturation, while minnow is least sensitive. The clinical symptoms of gas bubble disease in Atlantic salmon parr, such as subcutaneous emphysema, disappears within one week in 100% saturated water. Field studies indicate reduced fish density downstream of hydropower plants emitting supersaturated water and that tagged brown trout has limited ability to sense supersaturation. However, high levels of supersaturation cause lower mortality than expected from laboratory studies because mortality depends not only on dose but also on duration, frequency, dilution, aeration, and water depth. Unlike the fish studied in the lab, macroinvertebrates had a lower mortality caused by supersaturation. However, most invertebrates experienced buoyancy problems and floated on the water surface when the water was supersaturated.

Hydropower is predicted to increase by 73% worldwide in the next 10-20 years, and more data on the prevalence and impact of supersaturation on biota are needed to design more efficient mitigation measures in new and revised constructions.

Gas supersaturation at Norwegian hydroplants – risk modelling and monitoring

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ABSTRACT: Gas supersaturation from hydropower installations can harm aquatic life in rivers. The Research Council of Norway project SUPERSAT has assessed the risk of gas supersaturation in 1695 Norwegian hydroplants, based on turbine type, secondary intakes, and head. 444 hydroplants were identified as high-risk candidates. Subsequently, 10 hydroplants with the high risk were monitored with saturometer loggers. The results showed that total dissolved gasses (TDG) values of 110% were exceeded at all plants, with seven experiencing periods of TDG values reaching from 130% to 230%. Such high saturation can cause acute mortality and sub lethal effects in fish and benthic invertebrates. The findings suggest that severe gas supersaturation is more widespread in Norwegian hydroplants than previously thought. However, the ecological effects of gas supersaturation depend not only on the dose but also on duration, frequency, dilution, aeration, and water depth and require further investigations at each site.

Hydropower and hydromorphological impacts in freshwater pearl mussel (*Margaritifera margaritifera*) rivers: ecological bottlenecks and potential mitigation measures

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ABSTRACT: The freshwater pearl mussel (FPM) (*Margaritifera margaritifera*) is listed on the IUCN red list for endangered species as 'endangered'. Its populations have been declining throughout its range due to human pressures on river ecosystems. Under the EUs Habitat Directive, the species is recognized as a priority, and listed as such in Annexes II and V. It is an umbrella species and an excellent bioindicator meaning that its conservation will benefit the biodiversity and health of the rivers it inhabits. FPM is also a real ecosystem service provider dependent on viable salmonid fish populations to fulfill its life cycle. Norway represents a stronghold for the species and about 25 % of the remaining populations in Europe are located there (Larsen 2018). However, a third of the historically known populations of FPM in Norway have disappeared and 75% of the remaining populations are today not viable (Larsen and Magerøy 2019). Norway is also Europe's largest hydropower producer and the 7th largest in the world. Out of the 419 rivers with FPM in Norway, more than 70 are impacted by hydropower. Hydropower affects FPM both directly through alteration of its habitat or that of physico-chemical properties in the river, and indirectly, through impacts on salmonid host fish populations. In many rivers, hydropower is one of several co-occurring factors that have cumulative impacts on ecosystem functioning. It is therefore often difficult to disentangle the specific effects of hydropower from other pressures. In the case of the FPM, this kind of analysis has rarely been carried out.

One of the most widely implemented measures to mitigate hydropower related alterations in Norway is the release of a fixed minimum flow, with possible differences between summer and winter. Although a lot of studies have focused on habitat modelling and the effects of minimum flows for fish, much less is known about flow- and related hydromorphological requirements of FPM. We therefore argue that the effectiveness of minimum flows or ecological flow needs to ensure viable FPM populations is unknown. Addressing this knowledge gap is critical for the protection of this long-lived species, even more so in the context of multiple pressures like climate change and increased demand for flexible hydropower production. Here we present the results of a meta-analysis carried out using publicly available data on i) FPM population status, ii) hydropower mitigation requirements (e.g. level of Eflow), and iii) water framework directive related data, to establish the role of hydropower and related existing mitigation measures in affecting the status of FPM populations in Norwegian rivers. This includes assessment of the relationship between the intensity of hydropower impacts and the status of freshwater pearl mussel populations, as well as identifying ecological bottlenecks, possible suitable mitigation and management measures specially targeted for this species.

Connectivity, barriers, and integrated solutions

Fish passage facilities in a new hydropower plant at Hvammur in River Thjorsa, Iceland

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ABSTRACT: A new 93 Mw hydropower station will be built in River Thjorsa at Hvammur, South Iceland. River Thjorsa is partly a glacial river with average flow of 360 m^3/s. Already there are 7 power plants and reservoirs in the river system. All of them are up in the highland above Hvammur. River Thjorsa has a good run of Atlantic salmon, *Salmo salar*. The salmon population has increased in size for two reasons. One is that the river flow is more even, and the turbidity of the river water is lower as glacier silt stops in reservoirs where the river flow is regulated. The other is that a fishway was built in 1991 in the waterfall at Budi opened new parts of the river and doubling available habitat for salmon. Salmon is now inhabiting all these areas. The salmon population has been monitored for a long time. The annual run of salmon in Thjorsa last years has varied from 6 to 15 thousand salmon with the average of about 10 thousand salmon. A smaller run of sea trout, Salmo *trutta*, also inhabits River Thjorsa. Net fishing is the main fishing methods in the river, but rod fishery has been increasing.

Hvammur Power Plant will be located 55 km from the estuary. The river will be dammed forming a 4 km^2 intake reservoir. Number of fish migration measures will be taken to maintain the salmon run and the continuum of the biota. A fishway will be built in the dam. It is a vertical slot fishway with a slope of 1:13 and maximum height of head drop of pool 0,30 m and minimum flow of water 1m^3/s. A smolt bypass will also be built in the power plant. It is situated at the top of the intake to the power plant where 35 m^3/s of surface water will flow to the smolt bypass bringing the smolts gently to the river channel below the dam. Environmental flow below the dam is secured with minimum flow of 10 m^3/s. Monitoring program will be in place to evaluate the mitigation measures.

Turbine Design for Fish Inclusion

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ABSTRACT: Migration corridors for riverine species tend to overlap with valuable hydropower resources. Supporting clean hydroelectric power generation while also protecting freshwater diversity is in many cases an unmet challenge, but is essential to achieve true sustainability in hydropower. Exclusion infrastructure (i.e., fine fish screens, behavioral guidance infrastructure, and bypasses) may be utilized to protect fish from turbine entrainment, but also limits the available passage routes for fish and constrains hydropower generation. Alternatively, turbines designed to pass fish downstream safely and expediently can maintain connectivity for downstream migrating species while also enabling uninterrupted hydropower production.

Integrating safe downstream fish passage into normal hydropower operations through the use of fish-safe turbines can reduce cost and complexity while facilitating downstream migration of fish, opening the door to ecological sustainability in contexts where conventional fish protection techniques fail. We will describe the function and application range of the Restoration Hydro Turbine (RHT), which incorporates novel features and design techniques to achieve safe fish passage while maintaining conventional design constraints (high power density, high efficiency, low cost).

At the core of our understanding of the mechanisms responsible for safe turbine passage outcomes, and the bounds within safe passage is possible, is a rigorous research program crafted from the perspective of ecological and population-level impact. We will share RHT passage testing results for American eel (*Anguilla rostrata*), Alewife (*Alosa pseudoharengus*), and Rainbow trout (*Oncorhynchus mykiss*), which have shown a >99% survival rate for fish that would be able to pass through a conventional coarse trash rack. Consequently, the fish-safe RHT could serve as a useful tool and best practice for fishery management in watersheds where hydropower is present.

A new method for passing substrate over weirs

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ABSTRACT: Research conducted at NTNU in the 1990s focused on sedimentation and the development of sediment removal techniques based on the hydrosuction principle. This research initiative has led to the creation of various sediment handling technologies that are now utilized in over 30 countries within the hydropower and offshore industries. As a result, significant knowledge and expertise have been accumulated over the years in the field of sediment handling, encompassing functional solutions, hydraulic design, and material selection. Many of these technologies rely on gravity and have minimal moving parts, making them potentially applicable in river environments.

Among the latest advancements is the boulder excluder, a pipe structure that effectively transports sediments of various sizes from a brook intake (pond) to a lower downstream level, utilizing gravity as the driving force. The boulder excluder initiates its operation when the water level surpasses a certain threshold, typically during flood conditions, and ceases once the water level recedes. Remarkably, this technology operates without the need for any movable parts or human intervention and can function effectively even with very low head differences.

Consequently, it is highly plausible that this technology is well-suited for transferring different types of sediments or substrates from one location to another, particularly in rivers, for instance, bypassing artificial weirs in regulated river systems. Sediment transfer occurs through a fixed siphon, commonly implemented using a robust and durable HDPE-pipe, which activates during floods, drawing incoming sediments from an upstream pool to a lower downstream level. Additionally, this technology could potentially be employed to remove undesirable fine sediments from artificial pools, thereby providing an added benefit or parallel effect.

Evaluation of vertical connectivity in regulated river reaches using a multiparametric measuring approach

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ABSTRACT: The vertical connectivity in the hyporheic zone of alluvial rivers represents an important dimension for many aquatic species including macroinvertebrates but also for the reproduction of gravel-spawning fish. It is widely known that the infiltration and accumulation of fine particles into the riverbed (clogging) can severely impact the vertical connectivity, especially in regulated river reaches because of altered flow and sediment regimes. The process 'riverbed clogging' is also frequently named as a reason for failing the 'good ecological status' according to the Water Framework Directive (WFD).

Although the phenomenon 'clogging' has been studied for decades, no standardized quantitative and physical-based criteria are available to assess riverbed clogging. Available measuring methods range from qualitative approaches such as visual inspections (mapping) to single-parameter based approaches that are not sufficient to encompass the complex and interactive processes of clogging. Therefore, we developed a multiparametric approach (MultiPAC) consisting of measurements and analyses of particle size distributions, porosity values, hydraulic conductivities and dissolved oxygen contents (DOC). This novel approach enables a quantitative description of clogging and an identification of clogged layers in stratified riverbeds as the hydraulic conductivity and the DOC are measured in vertical profiles (over 50 cm sediment depth). We applied the approach before and after several restoration measures (artificial flushing and bed alterations) in a near natural by-bass channel and in a residual river reach. We could identify clear benefits of the measures in restoring the vertical connectivity, especially in the upper 15-20 cm of the riverbed.

Currently, we are working on the development of a rivertype-specific evaluation approach of clogging by investigating reference reaches in Germany (according to WFD) to obtain reference values for the measured physical variables of MultiPAC. Additionally, biological sampling including macro invertebrates and the interstitial fauna with subsequent DNA-analyses are conducted. Together with an assessment of catchment characteristics this concept results in a unique dataset that can serve as a basis for a quantitative evaluation approach of clogging. First analyses of the collected data show exciting findings regarding the degree of clogging and its abiotic and biological descriptions.

The benefits and challenges of using environmental nucleotides for fish passage species detection and enumeration

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ABSTRACT: Globally there is an urgent need to find solutions to balance energy-production and protection of vulnerable species and the maintenance of biodiversity. Although reliable and accurate ecological assessments are key to ensure protection of biodiversity, conventional biodiversity survey methods- electrofishing, seining, gill netting, snorkeling -rely on the physical capture or visual detection of fishes, which are costly, time-consuming, hazardous to personnel, cause habitat disturbance, and result in size, age, or species-biased estimates and misidentification. Newer, non-invasive methods such as environmental nucleic acids (eNA)- organismal DNA and RNA deposited into the environment from excretion, cellular discharge, and mortality- can be collected and analyzed from a water sample to identify species. Surveys using eNA thus have the potential to revolutionize species and biological community assessments, management planning, and decision-making procedures. In this study we used a combination of eDNA and eRNA sampling in the Grand and St. Joseph rivers in Michigan, USA, to determine if eNA can be a useful tool for species detection and enumeration in fish passages. We collected in total 678 samples across six dams and sampled upstream, downstream, and within fish passages across three months to characterize biodiversity before, during, and after spawning runs of potamodromous steelhead trout (*Oncorhynchus mykiss*), channel catfish (*Ictalurus punctatus*), and largemouth bass (*Micropterus salmoides*). We analyzed both eDNA and eRNA using 12s MiFish primers and CO1 primers for metabarcoding, as well as species specific primers for qPCR for four genes (12s, CO1, 18s, and CytB). We compared our results to Michigan Department of Natural Resources fish ladder counts and electrofishing data. Concurrently, we conducted mesocosm tank experiments to determine differential decays rates between eDNA and eRNA to provide a calibration metric for field eDNA/eRNA results. The findings from this work will serve as foundational information to support further investigation into eDNA/eRNA dynamics and the utility of eNA in fish passages and hydropower. Further, this work will demonstrate the application of eNA for biomonitoring, hydropower planning, construction, operations, and (re)licensing that could streamline processes by elevating our understanding of potentially impacted biota and informing and evaluating mitigation of environmental impacts.

Modelling fish recruitment potential of lithophilic fish in restored rivers by means of functional habitat and population dynamics modelling

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ABSTRACT: In hydropower impacted rivers the degradation of suitable habitats due to channelization, lack of sediment supply and interrupted longitudinal connectivity have strongly affected populations of rheophilic and lithophilic fish species, which rely on availability of gravel banks and shallow littoral zones for successful reproduction. The construction of nature-like bypass channels and bank restorations aim to mitigate these deficits by improving longitudinal connectivity and providing key habitats for early ontogeny, in particular for spawning, larval and juvenile development. Predicting and assessing long-term effects on fish populations following measure implementation is however challenging, because of complex recruitment processes acting at various spatial and temporal scales.

We developed an integrated modelling approach that links a functional habitat suitability model with a fish population dynamics model. The approach considers availability, quality and functional connectivity of the most critical habitats during early ontogeny, i.e. spawning and larval nursery habitats. Functional connectivity between suitable spawning sites and nursery habitats is estimated using a larval drift model simulating passive-active larval movement. The recruitment potential is finally assessed using a spatially-explicit fish population dynamics model, in which density-dependent survival rates for spawning and larval development are parametrized based on estimated carrying-capacities for eggs and larvae.

The presented modelling approach allows predicting recruitment potential of lithophilic fish species at existing and planned restoration sites,and can be applied to maximise recruitment potential by identifying habitat bottlenecks and defining optimal spatial shares of essential, functionally connected key habitats.

We tested the approach on a newly restored system at the Ering-Frauenstein Hydropower-Plant in the Inn River (South-East Germany) comprising both nature-like fishpass and restored side-channel downstream of the hydropower dam. Recruitment potential was estimated for four riverine, rheophilic, lithophilic fish species (*Thymallus thymallus; Chondrostoma nasus; Barbus barbus; Squalius cephalus*).

Session 6

Wednesday 14. June 2023

SUSHP 2023

Sustainability in Hydropower 2023

Reservoirs, their role in the future energy system and the effects of environmental contraints

Physical environmental impacts on a hydropower reservoir under different operational modes

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ABSTRACT: The world is facing a climate, energy, and biodiversity crisis. Norway, with almost half of Europe's reservoir hydropower storage capacity, can contribute to reaching the renewable energy targets by providing balancing services to the European market. Pumped hydropower storage (PHS) is the largest energy battery available worldwide and allows better integration of the volatile energy output of wind and solar power plants. In addition, refurbishment and retrofitting conventional storage power to PHS is being considered a profitable solution in today's market due to the high electricity prices. However, environmental effects are in general understudied. Under the HydroConnect project, physical impacts linked to environmental response are being investigated through a medium-term hydropower scheduling model developed by NTNU in collaboration with SINTEF to simulate the changes in water level and energy production under a PHS plant connecting to Norwegian reservoirs and compare it with the current situation under a conventional power plant. Water temperature has been in situ monitored to set up and calibrate a hydrodynamic model (CE-QUAL-W2) to evaluate temperature and ice dynamics under the current and the PHS operational mode. Results show that water level fluctuations are more frequent but with lower amplitude under the PHS operation, particularly in the lower reservoir with smaller volume. Under the spatial distribution analyses of the reservoir shoreline, it is possible to identify areas more susceptible to being dry and wet with higher frequency, which is linked to the morphology of the shoreline. Temperature dynamics and ice formation are mostly impacted at the surrounding of the outlet/inlet. Expected results will show how far from these structures the changes are propagated. In addition, the impact of different ramping constraints is being investigated. Increasing the knowledge about physical environmental impacts to analyse and recommend potential environmental restrictions will allow to better manage reservoirs under PHS operations, particularly when it can be linked to biological data.

Optimal Integration of Hybrid Pumped Storage Hydropower to increase renewables penetration and reduce CO_2 emissions

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ABSTRACT: Addressing climate change and energy crises is considered one of the world's greatest energy challenges. The presence of proven and reliable energy storage is fundamental to addressing climate change, which is needed to support intermittent renewable energy for a rapid transition of the energy sector from conventional fossil fuels to decarbonized energy sources. Solar and wind energy are both variable renewable energy sources. Their production is intermittent, which can be seen as an opportunity to be integrated into the pumped storage hydropower (PSH) system. Therefore, the main drivers for the massive development of PSH are the growing demand for variable renewable energy, the increasing demand during peak hours, and the modernization of plants to improve efficiency. This study investigates the benefits of integrating PSH and hybrid systems into the grid. Four schemes were tested in different seasons, including annual and daily distribution. The last scheme of daily simulation with an optimization solver is used to optimize the integration of PSH with a hybrid power system that uses solar and wind energy as primary renewable sources by minimizing the daily operating cost. The optimal value is determined from the minimized operating costs and the incoming and outgoing energy accumulation. The dispatch system includes load demand satisfaction considering the intermittent nature of solar and wind sources and demand fluctuations, presented with a hybrid system consisting of PV solar, wind turbines, PSH, and other power generation as a backup. The results show that using the developed model for optimal scheduling of PSH integration with renewables and the hybrid system each season, a significant CO_2 reduction of up to 84% can be achieved in summer at one of the proposed schemes. In comparison, daily costs can be reduced by more than 90% in all seasons. The two simplified NPV and payback period estimation models have shown that financing the project over 25 years is feasible with an interest rate of 10% for the combined PSH and hybrid system. With an optimized and adjustable scheme, the PSH can also provide a wider range of up and down ramps while modifying the power system in generation and pumping mode. A hybrid system combined with PSH can shift, store, and reuse generated energy until an appropriate load is available for system reserves and variable energy integration.

Acknowledgments

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Application of remote sensing for monitoring fish spawning sites of a large hydropower plant reservoir in a lowland region

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ABSTRACT: The main objective of a large hydropower plant (HPP) is to produce electricity, stabilize electrical grid and provide protection from floods at some level. Typically, operation of these large HPPs that use dams to store water in reservoirs is not an easy task, because at the same time it has ensure environmental protection requirements and fulfil other water users needs. Many studies had shown that peaking hydropower plants, play an important role for aquatic organisms and ecosystem. Reservoirs with shallow and gently-sloping littoral slopes as well as small shallow reservoirs can experience a greater magnitude of change of water quality due to water level fluctuations. Also, reduction in water level is likely to accelerate eutrophication processes and involves a higher risk of cyanobacteria blooms. Ecologically sustainable management of such reservoirs is especially difficult, because it has to combine a lot of different decisions that are opposing of each other and usually it is very hard to estimate the effects of ecological mitigation measures.

This paper is a short presentation of a research conducted in the reservoir of Kaunas hydropower plant (HPP) in Lithuania. It is a large, relatively shallow reservoir located in the Eastern European lowland (area 63.5 km^2, average depth about 7 m. The reservoir has two operating hydropower plants – Kaunas HPP and Kruonis pumped storage hydropower plant (PSP). To mitigate the impact on various aquatic organisms the Reservoir operation rules are in force that limit the operation of the HPPs. The main concern is to protect the fish spawning sites during spawning period. There is a lack of knowledge where those spawning areas are and how is their area affected when the water level fluctuates. A detailed survey of a small (about 5 ha) area containing several potential spawning grounds was carried out using Unmanned Aerial Vehicles (UAV) and traditional field survey methods to gather information and to track changes of the spawning grounds (drawdown areas). High resolution multispectral images were used to analyse the spectral footprint of aquatic macrophytes and the possibility to use the results to identify and map potential spawning sites in the entire reservoir was evaluated.

The aim of the study was to implement modern remote sensing techniques to investigate dewatering areas in the fish spawning sites. Surveying fish spawning sites that are containing aquatic macrophytes is typically a difficult task that is usually carried out by performing manual bathymetric measurements due to the limitations of sonars. Our hypothesis is that RS can be used to assist in surveying difficult and vulnerable areas, where the current and accurate data are needed. This knowledge could assist in making decisions for better use of reservoir storage while increasing power generation.

Assessment of Green LiDAR to map the bathymetry of lakes

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ABSTRACT: LiDAR stands for Ligth Detection And Radar technology and is a technique for detailed mapping of the Earth's surface. The LiDAR can be divided into two main types, the Red LiDAR which is based on the use of electromagnetic waves in the infrared wavelength specter (1064 nm) and can be used to map terrestrial areas. In contrast to Red LiDAR, the Green LiDAR penetrates water surfaces by using another wavelength spectrum, i.e. the green spectrum of electromagnetic waves (532 nm). This is a more complex and costly technology and has so far been less applied in Norway. Due to the field of application of Green LiDAR, it is sometimes denoted as bathymetric LiDAR, in contrast to the topographic LiDAR (Red Lidar).

The overall objective of this study reported has been to assess the suitability of Green LiDAR to map the bathymetry of lakes. The has been carried out by use of Green LiDAR data from three different lakes, i.e. Selbusjøen and Benna in Trøndelag and Krøderen in Viken, being the only lakes in Norway with Green LiDAR bathymetry data available. The assessment has been made by systematically compare the performance of different lidar sensors, as well as multibeam echosounder (MBES), against each other in those lakes where two or more datasets are available and spatially overlap.

The residuals while comparing multibeam (MBES) measurements with Green LiDAR measurements and Green LiDAR measurements against each other are generally very small, i.e., in most cases, much less than 10 cm, based on the mean and median residuals. When comparing different Green LiDAR sensors, the residuals are close and normally distributed around 0 cm, indicating no systematic error. The outliers in the datasets (large residuals, filtered out in some of the figures) have the highest representation in the outer range of the coverage, i.e., in very shallow water and close to the maximum penetration depth of the sensors.

Under perfect flying conditions and clear water, Green LiDAR seems capable of measuring down to more than 20 meters below the lake surface as in Lake Benna, while in most lakes probably less than 20 meters. Green LiDAR might be more suitable for mapping shallow parts of lakes, while MBES is more suitable for the deeper parts. In moderately deep areas, the two technologies seem both suitable and useful.

CoolHydro – mitigating extreme temperature events in hydropower catchments

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ABSTRACT: Water temperature is a key factor influencing biological activity and habitat suitability in freshwater systems. Many Norwegian River systems are hydrologically altered by hydropower regulation. A common plant layout is comprised of a reservoir and an underground penstock leading to a downstream power plant, often fairly distant from the reservoir. Release flows from dams are in many cases constant for extended periods and a large share of the natural discharge in summer and fall is not available in bypass sections. The resulting flows in bypass reaches are characterized by reduced water quantity and flow dynamics. Additionally, cold releases from high-altitude reservoirs can significantly alter the downstream temperature regime (thermopeaking).

In Norway, climate change is projected with increased precipitation in form of rain during winter and earlier snowmelt in spring, leading to a reduction in winter ice habitats both spatially and temporally. Additionally, more dry and warm periods may lead to cause more frequent and longer dry spells with peak temperature events. Water temperature peaks can be exacerbated in the bypass reaches under hydrological climate change: Low discharge rates and larger surface areas in these areas can result in increased net heat transfer compared to the natural, historical state.

However, well-timed hypolimnetic cold water releases from high-altitude reservoirs can help mitigate downstream peak temperature events.

This study aims to I. demonstrate a modelling framework for water temperature in regulated freshwater systems, II. assess the impact of climate change and hydropower regulation on river temperature in Nordic catchments and III. evaluate the effectiveness of adaptive hydropower operation strategies in mitigating peak temperature events. The study employs a distributed hydrological model, HYPE, calibrated using regional calibration and Differential Evolution Markov-chain routines to simulate discharge and water temperature using historical data. This model is coupled with a 1D lake model, MyLake, to simulate depth-distributed water temperature and ice behavior in individual reservoirs.

We focus on selected regulated and unregulated test case catchments and evaluate different historical and future water temperature scenarios downstream of hydropower plants and in the bypass sections. Downscaled CMIP5 climate forcing data of is bias-corrected and various release strategies are tested.

Preliminary results demonstrate satisfactory performance of the hydrological model in simulating discharge and temperature, with a bias to early-freeze up and delayed snowmelt.

An assessment of the impact of environmental constraints on utilization of Norwegian hydropower flexibility for integration of wind and solar power

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ABSTRACT: Utilization of hydropower flexibility carries an important environmental dilemma. Reservoir hydropower is a renewable energy source, generally with low GHG emissions, that can help balance the variability of wind and solar power and thus help achieve decarbonization of power systems. However, if the water flows depend solely on the power grid needs, potentially following hydropeaking patterns, it can lead to severe disruptions to downstream ecosystems and communities. Restrictions on water flows, referred to as environmental constraints, are therefore implemented. In Norway, these environmental constraints might become stricter in the upcoming years for the sake of preservation of the local environment. Meanwhile, the Norwegian hydropower flexibility has an important role in enabling a higher share of renewables with the ongoing energy transition. This study aims at quantifying the impact of environmental constraints on the capacity of Norwegian hydropower to balance variability of wind and solar power in the Nordic power system. Simulations are carried over this power system with the FanSi model developed by SINTEF. Based on detailed modelling of the Nordic and surrounding countries, the model uses a rolling horizon scheme to optimize economic dispatch in a stochastic environment. A sensitivity analysis is performed on the type and stringency of the environmental constraints. Special attention is also given to differentiating the impacts of these constraints when applied to hydropower reservoirs and plants with different technical characteristics. The variations in hydropower flexibility are observed through changes in the price patterns and resource utilization, as well as recourse to other dispatchable technologies, such as batteries and gas power plants. In order to maximize the climate change mitigation role of Norwegian hydropower while minimizing threats to biodiversity, careful selection of the type, location and level of environmental constraints applying to the power plants will be crucial.

Determining the hydrological implications of regulation on Swedish lakes with space observations

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Lakes and reservoirs are critical in providing freshwater resources and ecosystem services to agricultural and urban sectors. The storage and redistribution of water in these water resources for agriculture and energy production are known to induce important changes in the availability and variability of water by increasing evaporation from the artificial reservoirs and regulating the flow of water. For instance, hydropower development has been found to simultaneously increase the evaporative ratio in the hydrological basins and reduce the coefficient of runoff variation downstream, as natural peaks are suppressed. These effects induce significant physical and ecological impacts on dependent terrestrial and aquatic ecosystems. However, understanding the implications of regulations for downstream lakes is unfeasible, at least in the case of Sweden. With more than 100,000 lakes, Sweden has limited continuous gauged water level data in only 35 lakes, limiting the measurement of the impact of regulation on water levels. We here tackle this issue by using satellite Radar altimetry to track water levels in more than 100 lakes in Sweden from 1995 to 2022. We employ data from multiple altimetry missions, including ERS-2, ENVISAT, Jason-1,2,3, SARAL, Sentinel-3A, and Sentinel-3B. We find particular trends in water level that are dependent on the season. Furthermore, we find that changes in the trends, change, range and variability of water levels differ in regulated lakes from unregulated ones. We generate a map of changes for the entire longitudinal and latitudinal Swedish gradients. This study is the first assessment of a large set of water lake changes in Sweden and finds characteristic regulation signals on lakes. It also highlights the need to continuously monitor lake water levels to understand their ecological status and related impacts from climate change.

Plenary 5

Thursday 15. June 2023

SUSHP 2023

Sustainability in Hydropower 2023

Evident based solutions for sustainable management of hydropower impacts

IEA Hydro Annex on Hydropower and Fish: A Roadmap for Best Practice Management

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ABSTRACT: Hydropower has been recognized as a significant source of renewable energy globally, with an increasing number of countries investing in its development. However, despite its benefits, hydropower has adverse effects on the natural environment, and fish are one of the most affected animals in freshwater ecosystems. While the relationship between hydropower and fish has been extensively studied, there is still a lack of standardized, widely applicable solutions to address the challenges associated with their coexistence. This roadmap provides a framework for designing and implementing mitigation measures to address the impacts of hydropower development on fish and their habitats.

The roadmap suggests a multi-phased process for evaluating the need for fish passage facilities and other solutions at new and existing dams. The first step is to analyze the existing policies and requirements for addressing the impact of hydropower on fish in the country or region of interest. This includes understanding the legal requirements for mitigation measures and identifying any conflicts between policies and goals. The roadmap then provides sustainable options for further consideration and decision-making, including flowcharts as decision-support tools to guide readers through the mitigation option selection process. The final important step is to establish an operational monitoring program that evaluates the effectiveness of the selected mitigation option.

The roadmap provides a valuable resource for practitioners in the hydropower sector and other stakeholders involved in managing hydropower and fish. By addressing relevant measures to mitigate changes in hydro-morphological conditions, water quality and quantity due to hydropower development, the roadmap offers a clear pathway towards viable solutions for the identified challenges. While the main focus of the roadmap is to provide relevant and effective sustainable solutions for fish populations, many of the same measures may also be beneficial for other aquatic species and their habitats. With the continued global expansion of the hydropower industry, the roadmap's framework based on understanding the impacts of hydropower on fish will be crucial in improving the decision-making process for designing and implementing relevant mitigation measures. By doing so, we can promote the sustainable development of hydropower while minimizing its impact on the environment and its inhabitants.

The roadmap was published in April 2023, and is available for download here Hydropower and Fish - a Roadmap for Best Practice Management | Zenodo

Restoration of flood-maintained ecosystems

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ABSTRACT: The ECOPEAK project was initiated in 2019 as a part of the research and innovation program Hållbar Vattenkraft (Sustainable hydropower) – HåVa at the Swedish Energy Agency. The purpose of the project is to develop management methods to restore riparian communities in Natura 2000 areas in rivers used for hydropower production. In the project we analyse the potential for reintroducing short high-flow events mimicking seasonal floods to enhance the processes creating and rejuvenating riparian habitats with high natural values along regulated rivers. We evaluate the efficiency of different peak-flow scenarios to create habitat using hydraulic modelling based on empirical flow-ecology relationships.

We have focused on riparian areas in the middle parts of Klarälven and the lower parts of Dalälven in Sweden as these reaches have some of the highest riparian natural values in Sweden. At the same time, they are affected by large scale hydropower and are important components of the Swedish energy system. Typical flow alterations in these rivers consists of diminished or lacking spring floods, and higher winter flows compared to unregulated conditions. There is also impact from hydropeaking in these reaches. In Klarälven, the high natural values are linked both to flood dynamics and to erosion and sedimentation dynamics in the meandering river channel. The red-listed *Salix daphnoides* and *S. triandra* are signature species that grow on the sandy point bars. However, the point bars have declined in extent due to regulation. The Lower Dalälven has some of the highest natural values in Sweden in terms of riparian ecosystems. With its diversity of habitats listed in the Species and Habitats Directive, these are unique areas with many red-listed species. Due to reduced high-flow peaks, species such as Norway spruce may out-compete species associated with the floodplain forest, leading to narrower riparian areas with lower species richness. These habitats are thus dependent on recurring floods, but it is not clear how frequent and long these floods need to be.

In order to better understand the relationship between flooding regime and floodplain vegetation we explore hydraulic conditions and construct probability curves describing preferred occurrence of riparian species according to flooding regime. Additionally, we create response curves describing survival and growth for tree species present in the riparian zone. Further, we make predictions of the unregulated extent of different vegetation belts (aquatic, graminoid, *Salix,* and riparian forest) based on vegetation belt distribution data from the unregulated Vindel River together with modeled unregulated flow regime. We compare the current extent of the different vegetation belts to pre-regulation extents in order to make deficit analyses for the habitat types. Finally, we determine the frequency and duration of inundation needed to create different vegetation belts associated with high riparian natural values, and to ensure the presence of specific plant species of high conservation value.

USING TURBULENT EDDIES TO GUIDE FISH: THE FISHPATH PROJECT

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ABSTRACT: The continuing increase in global energy demand, and the need to mitigate anthropogenic climate change by increasing renewable energy shares, are drivers for major changes and growth in the hydropower (HP) sector. At the same time biodiversity is declining at an unprecedented rate and sustainability can only be achieved through transformative changes. Thus, the global HP industry faces the challenges to increase renewable energy production while simultaneously protecting biodiversity.Habitat fragmentation due to the presence of HPPs, dams and weirs is one of the major threats to worldwide aquatic biodiversity. Maintaining or re-establishing longitudinal connectivity for fish in fragmented rivers is then crucial. These drive for knowledge-based optimized solutions. The FishPath (Turbulent eddies to create paths for safe downstream migration for salmonids and eel past hydropower intakes) project proposes at developing an innovative eddie-based guidance structure to facilitate downstream migration of fish passing hydropower structures. The novel idea is that knowledge on fish behavioural responses to turbulent eddies can be used to develop guidance system to create alternative migration pathways for fish around HPP. Current solutions are challenging in terms of technology, operation and costs. FishPath outcome is expected to be a practical solution applicable in a wide range of rivers with different types of hydropower. In this presentation we will give a summary of the project and the main results so far obtained focusing fish behaviour- eddies interaction.

A critical review of best practice mitigation towards low ecological impacts from large hydropower in Europe and the US

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ABSTRACT: The international community is facing multiple crises today, including the climate crisis (IPCC, 2021), the nature crisis (IPBES, 2019), and in some regions the energy crisis (IEA, 2022). The challenges are complex and the UN has agreed on a set of sustainability goals that all countries are targeting until 2030 respectively 2050. To address these goals, the EU has created the Green Deal: a set of strategies and regulations that aims for no net greenhouse gas emissions by 2050, decoupling economic growth from resource use, and leaving no person or place left behind. This includes the Taxonomy of Sustainable Finance's Do No Significant Harm (DNSH) criteria, that is, activities addressing one or more of the six EU Taxonomy objectives must also do no significant harm to any of the other. For electricity from hydropower (HP) to qualify as sustainable, needs to meet specific criteria related to protection of biodiversity and ecosystems (by following the river continuum concept), and halt greenhouse gas emissions. In this review, based on expert judgement we compiled large-scale HP projects from Austria, Norway, Portugal, Switzerland, and the US, with a high likelihood for low ecological impact due to best practice mitigation solutions. These HP projects are selected because they have modern licenses with ambitious mitigation measures, at least regarding individual ecological impacts. Some of these projects will effectively serve as pilot sites for sustainable solutions, and be among the first of their kind in the world for supporting riverine ecosystem functions. The main objectives of this study are to i) highlight modern solutions for mitigating HP impacts, ii) compare environmental performance of new mitigation measures to current standard practice and iii) discuss if the compiled cases are all likely to meet sustainability standards. In this study we compare the level of sustainability and whether we seem to have a common understanding of the best available mitigation strategies for large-scale or complex hydropower projects. All cases have environmental flow or ramping requirements, and their complexity varies based on plant characteristics. For example, some plants may have flow requirements to mitigate hydropeaking while others will be addressing flow alterations in by-passed sections. Several of these cases have mitigated hydropeaking either by retention basins or by operational ramping restrictions, to significantly reduce stranding and flushing of riverine biota. Alternative technologies like huge batteries and optimalization algorithms are feasible solutions in some of the cases to make hydropeaking more sustainable. Other cases have been required to mitigate thermal alterations,

by installing dual lake reservoir intakes. Safe fish migration aids are implemented where relevant. An important mitigation potential in several of the cases are related to multiple stressors affecting river ecosystems, as not only flow alterations affect biota, but also habitat availability. Thus, the establishment or restoration of suitable habitats, e.g. by river widening, reconnection of tributaries or management of spawning grounds, may be needed to ensure sustainable populations of riverine biota in the HP impacted rivers.

Opportunities and challenges for sustainable hydropower in the European Union and in Europe

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ABSTRACT: Hydropower provides an important contribution to renewable energy, with multiple benefits associated to water reservoirs. However, it can also cause considerable environmental damage to river ecosystems. Hence sustainable hydropower needs to achieve a good balance between electricity generation, impacts on ecosystems and benefits on society, supporting the achievement of the Green Deal targets and the objectives of renewable energy and water policies. Several sustainable hydropower options exist, whose potential is of high relevance especially in the European Union. Amongst others, these are: modernization of the existing hydropower fleet, hydropower integration and hybridization with other energy technologies (floating photovoltaics, heat extraction from generators, batteries), tapping hidden hydropower in water and wastewater distribution networks, hydropower in existing and non-removable barriers (e.g., water mills), reservoir interconnection and hydrokinetic turbines. Digitalization is also emerging as a relevant strategy to mitigate impacts along rivers and optimize hydropower generation taking into account weather, technical, market and environmental factors.

Flexible hydropower ensures the security of electricity supply - Growing challenges due to accelerated climate targets and energy crisis

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ABSTRACT: Based on the study "Status and Future of Alpine Hydropower", the Working Group Alpine Hydropower (Arbeitsgemeinschaft Alpine Wasserkraft, AGAW) published the subsequent study "Hydropower & Flexibility, the contribution of Alpine hydropower to the success of the energy transition" in late 2019. As a result of the rapidly progressing climate change and the increased efforts to achieve the climate goals, the EU and its member states have agreed on fast implementation strategies following the European Green Deal. At the same time, there were rapid upheavals in the energy market due to unexpected geopolitical changes in 2022, resulting in the energy crisis.

With the focus on the updated expansion targets according to the national energy and climate plans, the increased flexibility requirements of hydropower are described. With the increasing expansion of volatile power generation from wind energy and photovoltaic systems, power generation will be subject to even greater fluctuations in the energy grids system in the future. Actually a lack of flexibility in power generation is ensured, at least temporarily, from gas-fired power plants, until there is a sufficient supply of regeneratively produced hydrogen. Nowadays, this option must be reconsidered with the increasing uncertainty in the supply of natural gas. The resulting lack of flexibility can only be compensated for by increasing the share of pumped storage.

Thus, in order to ensure the necessary balance between electricity generation and consumption in the energy transition towards a CO2-neutral future, the expansion of energy storage is also absolutely necessary. Pumped storage power plants hold a prominent position among electricity storage technologies because of their large-scale and proven application. The possible contributions in this regard and the potentials that need to be realized in the Alps are described. In addition, the possibilities and advantages of pumped storage for future requirements in terms of control energy, frequency control and the capacity market are presented. Implemented examples of how this flexibility can be provided today are highly modern pumped storage power plants, whose enormously flexible technical capabilities are demonstrated (e.g. AT: Kopswerk II, Obervermuntwerk II, Kühtai I + II, Limberg II, Reisseck II, CH: Grimsel 2, Linth-Limmern, Nant de Drance, Veytaux, FR: Bissorte, Grand-Maison, Le Cheylas, Montézic, IT: Edolo, Entraque, Ponale, SLO: Avče).

The production of flexible energy causes frequent changes in discharge, i.e. hydropeaking. In order to mitigate the effects of hydropeaking comprehensive research projects were carried out especially in Austria and Norway – from process understanding towards the development of sustainable measures. In order to reduce the ecological impact of hydropeaking, measures such as hydropeaking diversion HPPs, retention basins as well as operational measures (combined with hydromorphological measures) are foreseen according to the implementation of the Water Framework Directive (WFD) and corresponding River basin management plans (RBMPs). Regarding hydropeaking diversion HPPs the project GKI has pilot character in the alps. Regarding retention basins, examples from Austria (Silz, Inn river), Italy (St. Anton, Talfer) and Switzerland (Innertkirchen, Hasliaare) represent best practise. Operational measures can include the use of impoundments to buffer hydropeaking waves. Other operational measures at flexible HPPs are not feasible, as flexibility of hydropower ensures the integration of “new renewables” (wind, PV) and are the key factor for successful energy transition.

Regarding pumped storage power HPPs the advantage is, that they can be also operated as a closed system, i.e. turbining/pumping from an upper to a lower stage and backwards, which reduces hydropeaking towards receiving waters. However, storage hydropower with high heads might be not feasible for pumped storage and require suitable hydropeaking mitigation. The case studies presented herein, underline that the hydropower sector develops suitable measures to ensure energy security and sustainable operation of hydropower plants.

Sustainable sediment management for hydropower: Results of the CD-Laboratory “Sediment research and management”

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ABSTRACT: It is predicted that 60% of all new energy investments over the next 20 years will be in renewables. The estimation for new hydropower production is 25% of all new renewables primarily due to potential in China, Africa, Latin America and South-East Asia. Also in Europe, a growth of hydropower production is aimed to achieve emission targets within the European Union by 2050. However, one of the main economic, technical and ecological challenges in future are the deposition, the treatment, and the disturbed dynamics of sediments in river catchments, which reduce the future market potential of hydropower significantly. Due to a lack in awareness of those sedimentological challenges (e.g. lack of process understanding), various huge economical, technical and ecological problems emerge with an increasing relevance for hydropower industry, water management authorities and the society in future.

The CD-Laboratory “Sediment Research and Management” aims to establish and preserve the long-term use of reservoir capacities, and a long technical lifespan of various plant components, such as intake channels, pumps and turbines. Moreover, the preservation of given flood protection (due to reservoirs) like peak flow retention and the important flood storage capacity will be targeted. Module 1 aims to improve the economical, technical and ecological standards for hydropower use. Module 2 focuses on the improvement of the sediment management for industrialised rivers, and Module 3 targets to achieve a long technical life span of various plant components. However, all these issues will be addressed within the framework of the overall aim to minimize the costs in future by improved sediment management in alpine regions and industrialized river catchments. Based on the determination of the state-of-the-art engineering practice, basic research is conducted concerning erosion, transport, sedimentation and remobilization of bedload and suspended load sediments. Here, a combination of both laboratory (e.g. flume experiments, physical models) and field studies (e.g. monitoring of reservoir flushing) on different scales (µm – catchment) enable an improved process understanding. Moreover, based on the development or adaptation of hydrodynamic-numerical models and monitoring techniques (e.g. seismic profiling), advanced tools are provided for the national and international hydropower industry.

The outcomes of this CD-Laboratory provide new standards for technological, ecological and economical optimization of hydropower management and novel aspects for a sustainable sediment management in industrialized rivers based on (i) advanced process understanding, (ii) environmental impact assessments, and (iii) the development of new monitoring / modelling technologies. Further it is targeted the results from the CD-Laboratory “Sediment Research and Management” in strategy plans, guidelines, manuals, natural water safety plan and into laws, and a significant contribution to a consistent Austrian strategy concerning the future sediment management in surface waters, in cooperation with all federal groups working in the field of mountain- and hydraulic engineering.

Research priorities in hydropeaking

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ABSTRACT: Peak-operating hydropower and hydropeaking have received increasing attention in the last two decades. However, knowledge gaps remain, and the transfer of science into mitigation actions and policy-making is still scarce. In this study, we undertook an online survey available in six languages to gather open research questions from more than 200 hydropeaking experts across the globe. We then used a systematic method of determining expert consensus, the Delphi method, to identify the top 100 key questions out of over 400 submitted ones related to eight thematic fields: (i) hydrology, (ii) physicochemical properties of water, (iii) river morphology and sedimentology, (iv) ecology and biology, (v) socioeconomic topics, (vi) energy markets, (vii) policy and regulation, and (viii) management and mitigation measures. The high-priority questions agreed upon by consensus target research objectives that are both achievable and answerable, covering a broad range of topics. The list of questions thereby serves as a useful tool to direct researchers towards enhancing the science-policy interface, aiming to bolster the sustainability of peak-operating hydropower in diverse geographical and socioeconomic settings.

Overview of U.S. Department of Energy's Water Power Technologies Office R&D to Advance Sustainable Hydropower

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ABSTRACT: An overview of research and development supported by the U.S. Department of Energy's (DOE) Water Power Technologies Office (WPTO) will be presented focusing on the Hydropower Program's priorities for sustainable hydropower. The WPTO strives to ensure that hydropower's contributions towards meeting U.S. energy needs are consistent with the objectives of environmental stewardship and water use management identified in the 2017 *Hydropower Vision Report*. Information on recent competitive funding awards relevant to sustainable hydropower operations will be shared (e.g., improving fish passage, real-time monitoring, Artificial Intelligence, sensor systems). Additional information on governmental priorities for climate, environmental justice, and renewable energy will be noted. A case study demonstrating how 15 federal agencies are coordinating across diverse mission spaces in a Fish Passage Task Force to improve watershed-scale and community benefits of the record funding made available by the 2020 Bipartisan Infrastructure Law for hydropower environmental improvements, dam removal, and aquatic restoration will be presented.

Posters

Biotic alteration of benthic macroinvertebrate communities based on multispatial-scale environmental variables in a regulated river system of Kashmir Himalaya

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ABSTRACT: The Run-of-River (RoR) hydropower projects change the natural flow regime and impact the ecology of the river ecosystem. Assumptions of eco-friendliness surrounding RoR hydropower plants have been rarely tested. Keeping this knowledge gap in view, the present study was undertaken to understand the impact of ROR power plants on the macroinvertebrate assemblages in the Sindh River Basin of Kashmir Himalaya. Multivariate statistical techniques were employed to understand the relationship between dynamic patterns and variability in diversity (Alpha and Beta), abundance and pattern of macroinvertebrate assemblages and environmental factors. Non-metric multidimensional ordination plot (Bray Curtis index) revealed that taxa composition differed among sites, and to a lesser extent among seasons. β-diversity evaluation at spatial scale revealed a significant difference between sites based on abundance data, but the difference was pronounced using presence-absence data. Betadisper and Adonis's test indicated that the sites are homogeneously dispersed (distance to centroid) about taxa studied while having significantly different compositions. Alpha-diversity metrics (Shannon) along the gradient of Sindh River, is largely explained by the variations in substrate types and Total Solids (TS) while the variance in macroinvertebrate assemblage (beta diversity) to a large extent is explained by altitude (alt), discharge, and medium-large cobbles (MLC) throughout the study area. Based on relative abundance (%), the upper turbulent and unregulated sites (S1 to S6) characterized by cobble and gravel were found dominated by Deuterophlebiidae, Tipulidae**,** and Blephariceridae while Simulidae, Gammaridae, and Chironomidae had a greater preference for lower sites. The hydrological modifications resulting from RoR hydropower plants showed clear impact on beta-diversity and other macroinvertebrate assemblage patterns at regulated stretch (S7 and S8) and downstream reaches. Furthermore, Bray-Curtis and Jaccard's metrics results demonstrated that sites in the regulated stretch (S7 and S8) have higher similarity in terms of macroinvertebrate diversity and abundance. Regulated (S7 and S8) and downstream site had higher percentage of collector functional feeding group compared to the other sites. The present study provides valuable information on the effects of environmental factors and river regulation on macroinvertebrates assemblage patterns critical for effective management and restoration of river ecosystems.

Keywords: Rivers; Macroinvertebrates; River regulation; Run of river hydropower plants; Indian Himalayan Region

Building a national-scale dataset of fish passage infrastructure at hydropower facilities in the United States

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ABSTRACT: Environmental sustainability has become an existential criterion for hydropower facilities – hydropower cannot be considered an eco-friendly technology if it does not provide for basic river functions such as the passage of aquatic organisms. Hydropower dams can act as aquatic barriers to the upstream movement of migratory fish in rivers, reducing population connectivity within watersheds as well as restricting access to habitat to complete complex life history stages. Further, the operations of hydropower facilities, particularly during downstream migration, may cause fish to suffer injury or mortality while attempting to pass through energy generation turbines, from impingement on barrier screens, or while passing over large spillways. Fish passage infrastructure is used to mitigate risks of hydropower dams and operations to migratory fish, but information on the location, types, characteristics, and costs of such infrastructure are incomplete at a national scale in the United States. In partnership with US federal agency and industry stakeholders, we are creating a georeferenced dataset of fish passage infrastructure at US hydropower facilities. This dataset will contain attribute information that is desirable to a diverse range of stakeholders, including data on passage infrastructure and technologies, engineering characteristics, targeted fish species, operations scheduling, estimated costs, and passage performance studies. In addition, non-public information on passage infrastructure, including engineering characteristics, operations, and cost data, will be collected using online surveys of owners/operators of hydropower facilities. Products from this project will address a large gap in knowledge of the deployment of fish passage technology and be freely available to the U.S. hydropower community (i.e., Federal and State regulators and resource agencies, non-governmental organizations [NGOs], Industry members, and other stakeholders) to aid in project planning and regulatory licensing activities. This work will support the development of decision support tools and information to improve environmental performance and ensure hydropower's long-term value as a flexible, renewable energy resource.

Patterns of biodiversity impact caused by hydropower-induced environmental variability. Studying littoral zone community dynamics

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ABSTRACT: Hydropower with reservoirs may be integral to the increase of global renewable energy production. It complements intermittent renewables like wind and solar with its ability to store water and thereby regulate power production. However, this variation in production also significantly alters variation in environmental factors affecting biodiversity. Particularly by leading to degradation of the littoral zone in reservoirs. This exemplifies how sustainability measures may come in conflict, specifically those targeting the nature and climate crisis. In order to minimize conflicts in future planning of hydropower development, we need more knowledge on what areas are the most/least affected by regulation.

The aim of my PhD project is to understand how hydropower-induced environmental variation affects lake littoral communities along biogeographic and environmental gradients. This will be achieved by upscaling biodiversity knowledge from local to regional levels to identify possible patterns of impact, focusing on Fennoscandia.

The methodology is centred on the utilization of historical and more recent species/taxon occurrence data from benthic invertebrate communities, mainly sourced from the Global Biodiversity Information Facility (GBIF). The project will 1) look at patterns of impact on benthic invertebrate communities on a regional scale (Fennoscandia), 2) link the effect of hydropower-regulation on littoral communities to lake food webs using fish stomach content- and stable isotope-data from the NTNU University Museum and collaborators (Norway), 3) perform a field-study including 6 Norwegian lakes to study community dynamics with a higher spatiotemporal resolution (Trøndelag county, Central-Norway).

The expected results from my project may contribute to the understanding of critical pressures on freshwater biodiversity and the identification of pathways for environmentally friendly hydropower production.

This PhD is one of seven PhD positions at the NTNU Sustainability project named SusHydro - *Sustainable hydropower development and reservoir management as an enabler of the renewable energy transition and an accelerator to meet the UN Sustainable Development Goals (SDGs)*. My work will be integrated with the findings from the SusHydro group, with the goal of identifying interdisciplinary solutions for improved practices and sustainable hydropower development.

Effects of water level regulation on aquatic insects in reservoirs

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ABSTRACT: Hydropower with reservoirs is a renewable and flexible way of producing energy and will become increasingly important as the energy grid is decarbonised to combat climate change. Unfortunately, the development and operation of hydropower can also have severe negative environmental impacts, and it is imperative to understand and potentially mitigate these effects. A natural lake experiences environmental variability, e.g. in the form of fluctuations in water level and temperature, and the organisms living in the lake are adapted to tolerate or respond to these patterns of fluctuation. When a lake is regulated for hydropower purposes, this changes the patterns of environmental variation. The water level fluctuations can increase in amplitude, as well as show altered frequency and timing. This can affect organisms living in the lake, and organisms in the littoral zone may be especially susceptible for changes in the water level fluctuations.

The aim of this project is to find out how changes in water level fluctuations affect the phenology of invertebrate species in the littoral zone, and if different life history traits may contribute to explaining why some species are more affected than others. A selection of regulated and unregulated lakes in Trøndelag, Norway, will be surveyed to investigate 1) differences in species composition of aquatic insects between regulated and unregulated lakes, 2) if these differences are correlated with life history traits, and 3) if the phenology or life history traits are different within species that are observed in both types of lakes. This will be complemented by a theoretical optimisation model and simulations, to assess which mechanisms and environmental variables are important and likely to cause the observed results. By including options for different models of hydrology, climate change, electricity mixes and environmental constraints on hydropower operation, the theoretical model could predict species responses in a range of scenarios for present and future operational use of hydropower. Understanding the details of how different patterns of environmental variation affect organisms living in reservoirs, might help us to identify suitable mitigating measures to minimize trade-offs between conserving biodiversity and other aspects of hydropower management.

Flood Control by Reservoirs in Nea Basin

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ABSTRACT: Norway is a country that generates power mainly from regulated hydropower systems. The Norwegian hydropower system has a large reservoir capacity and a potential for flood control by taking benefit of empty capacity in the periods of high runoff. As such, river basins regulated for hydropower benefit from reduced flood peaks and volumes and reduced societal losses during extreme flood events. Nea river basin is a highly regulated basin that consists of several regulatory reservoirs. The flood control of reservoirs in Nea basin was assessed in this study. The highest flood control is observed in the years of 1988 and 2013 whilst the lowest occurred in 1988 and 2005. The flood control by reservoirs in Nea basin is higher in the Spring season. The different regulations of reservoirs are the reasons to have fluctuations in the flood control by reservoirs throughout the seasons.

Accounting for biodiversity trade-offs from hydroelectricity production in Life Cycle Assessment

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ABSTRACT: The expected expansion of hydroelectricity production in future energy scenarios[1] shows that hydropower remains an important technology to achieve the United Nation's sustainable development goals (SDGs) on affordable and clean energy and climate action. However, the construction and operation of hydropower plants have significant environmental impacts, which interfere with the SDGs for life on land and clean water due to biodiversity trade-offs. The poster addresses the topic of balancing synergies and trade-offs arising from hydroelectricity production.

Life Cycle Assessment (LCA) is a tool that allows for a comprehensive evaluation of the environmental impacts associated with the entire life cycle of hydropower plants, from raw material extraction to decommissioning. LCA can contribute to the debate on how to design a renewable energy system, as for example onshore wind and hydroelectricity production can be compared in terms of environmental impacts. Furthermore, LCA can be used to minimize the environmental impacts through strategic site selection of future hydropower plants.

LCA case studies on hydropower have often neglected biodiversity impacts. Life Cycle Impact Assessment (LCIA) models are required to quantify biodiversity impacts and many still need to be developed. The biodiversity trade-offs associated with hydropower development concern freshwater, marine, and terrestrial species and arise in all life cycle stages. Dorber et al.[2] were the first to develop LCIA models for the impacts of land use change, water evaporation, and GHG emissions arising in the operation phase of hydropower plants.

The poster will discuss a framework to consider the remaining environmental impacts, such as river fragmentation, invasive species, discharge regulation, sediment trapping, and temperature changes. Many of these impacts are confounded, e.g., low discharge levels can result in fragmentation, as well as limited access to spawning habitats, increased temperatures, and stranding of species.[3]

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HyPeak: a science-policy network to promote sustainable hydropeaking

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HyPeak is an international non-profit, volunteer-based network aiming to translate the results of hydropeaking research into practice and policy. This includes a multi- and interdisciplinary approach to tackle hydropeaking impacts, propose mitigation strategies, and support decision-making on hydropeaking-based hydropower. However, bridges across disciplines remain to be developed, particularly regarding the social and economic sciences, whose links with the biophysical research have yet been weak. Finally, the transnational viewpoint of HyPeak is crucial for researchers, policy makers and practitioners, as both river management and electricity markets need cooperation and knowledge exchange across borders. The network seeks to promote more sustainable hydropeaking by advocating state-of-the-art mitigation approaches. To this aim, HyPeak fosters the following research topics: i) the assessment of environmental effects and related socio-economic issues at various spatial and temporal scales; ii) the improvement of mitigation measures and management strategies; iii) the promotion of environmentally-sustainable approaches to hydropeaking; iv) recommendations for national and international policies, and the support for their integration. To develop this type of effective research, we have identified six high-priority tasks: i) compile an overview of the localization and typology of hydropeaking at a continental scale; ii) standardize tools characterizing hydropeaking regime, iii) identify the most informative indicators for assessing hydropeaking impacts, iv) advance the development of technical approaches to limit the negative impacts of hydropower plant operation on river ecosystems, v) elaborate inter- and transdisciplinary approaches to find a compromise between ancillary, balancing and flexibility services to the grid and ecological sustainability, vi) improve the efficiency of the knowledge and tool transfer between researchers and practitioners.

WFDs Environmental Objectives and Hydropower in Sweden: An overview of and general principles for levels of ambition

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ABSTRACT: County administrative boards that are water authority are responsible for the setting of environmental objectives according to the water framework directive (WFD). We will present a summary overview of the current environmental objectives for water bodies in Sweden that are impacted significantly from hydropower. This overview will report the different levels and classes of environmental objectives including the application of designation of heavily modified water bodies (HMWB) and the use of exemptions (less stringent environmental objectives according to art.4.5 and extension of deadline according to art. 4.4 in the WFD).

The main principles used in Sweden for assignment of different environmental objectives and designation of HMWB will be explained thereby illustrating the level of ambition. This includes the assessment of “significant adverse effects” on power generation based on, among others, the impact of environmental measures on power production and balancing capacity. It also includes compliance with objectives originating from other EU directives such as Natura 2000.

The role of environmental objectives and actual status and results, within the 20-year process for the revision of the hydropower plant licenses (the National Plan for Modern Environmental Terms) will be discussed for current environmental permit revisions for some example catchments.

Closing

Thursday 15. June 2023

SUSHP 2023

Sustainability in Hydropower 2023

Concluding remarks

Closing remarks by Jakob Granit, Director General, Swedish Agency for Marine and Water Management

SUSHP Sustainability in Hydropower 2023 – Ecological mitigation, best practises and governance

Trondheim, Norway, 13-15 June 2023

- I am very glad to be able to provide some closing remarks to this terrific conference.

- On a lighter note, I think I speak of all participants in thanking you for your great Norwegian hospitality and all the arrangements you have made to make this conference a success.

- Extra thanks go to Professor Tor Haakon Bakken and Chief Engineer Jo Halvard Halleraker and your teams – we have seen you working very hard to teach us use the microphone and to manage us numerous presenters and moderators. A great task and always on time and with a smile!

- The entertainment has been first class with the conference dinner at the Royal Garden with the Beatles inspired band “Algorithm” and the beautiful music pieces played on the Grand organ at Nidarosdomen Cathedral.

- Again we are very happy that this conference is referred to as a follow up conference to the sustainable hydropower conference arranged in Northern Sweden in June 2019 arranged by my agency and the County of Norrbotten – we have established a good tradition.

- On a more serious note, let me provide some reflections on what we regard as key outcomes of the conference.

- First of all, from a theoretical and practical perspective related to management of HEP there have been many papers presented demonstrating that collectively we have much knowledge of how hydropower effects our ecosystem in the short term and in the long term.

- We have also identified research gaps which was clearly demonstrated during the poster presentation session by the PhD students. For example new research on accounting for biodiversity loss in reservoirs and the important role of riparian vegetation.

- At the same time we have also gathered knowledge on how to mitigate some of the negative impacts on the ecosystem. Practises presented in detail include rebuilding river systems continuum, re-creating connectivity for living organisms, overcoming fragmentation and restoring water dependent ecosystems to safeguard biodiversity.

- Papers presented in this conference provide solid evidence for this. The question we may ask ourself, however, is if a piece meal approach to making hydropower sustainable project by project is good enough? Can we move faster? Do we have governance and management gaps?

- Contrary to building the new blue economy in the marine space, that I referred to in my opening statement, for example through marine spatial planning, zooning and strategic environmental assessment for off shore wind, we do not seem to have that opportunity in our river basins.

- Secondly, in parallel to the effort put in place to reduce the impact of HEP on our ecosystems there is an increased demand for renewable and fossil free electricity production also serving electricity systems flexibility services.

- This was demonstrated in the Swedish case with the foreseen doubling of electricity production and at a global level with the tripling of electricity production from hydropower.

- This to meet the green energy transition as we heard in the EU and USA meeting our climate targets and the need to meet demands for modern energy in developing regions.

- We must also remember that according to the latest IEA data, the number of people around the world who live without electricity has risen by nearly 20 million in 2022, reaching nearly 775 million, the first global increase since the IEA began tracking the numbers 20 years ago.

- There are thus many efforts ongoing to build new sustainable hydropower, both very large hydropower to serve electricity needs and systems services on international grids as well as small scale HEP schemes.

- Papers presented demonstrate that the cumulative environmental effect of many small HEP can be larger than from larger HEP projects that also include pumped hydro.

- Even though northern Europe may gain more rain because of climate change weather patterns are also becoming more erratic and dry spells and even droughts are also becoming a new normal in Northern Europe. This topic did not gain much attention in the conference.

- Finally, you may recall that I in my introduction I called for a wider system approach in which we put the river basin and the catchment at the heart of the management of water resources – ecosystem based management. Multipurpose storage need more attention.

- It seems from several papers in this conference that we may ask ourself if we are really successful in such an approach? Our common WFD which sets the governance framework seems to be implemented differently at the management level amongst the EU member countries.

- In some member states new hydro is being built in others there is a struggle to reach GES. The focus on water bodies rather than catchments and a high level of regulatory demands is a complex proposition to implement in many places.

- An even wider system approach is to understand the whole hydrological cycle from source to sea which was also raised during the conference. Management of hydropower plants and other barriers in the ecosystem is designed to increase the passage of fish such as salmon, the European eel and the Sea lamprey.

- But even if we succeed in restoring their river and lakes habitats fishing patterns also need to be managed in the open sea. The regulation of the Baltic salmon fishery in the open sea brought the salmon back to the rivers for spawning - a successful management approach – but for the sea lamprey that depend on large fish as a host in their life cycle their host is now over-fished.

- The source to sea context also brings the issues of important sediment transport to the coastal zone for erosion prevention and the transport of nutrients to the coastal system into the equation. At the end we are dealing with connected ecosystems which has been clearly articulated in the conference.

- In conclusion, this conference demonstrate that water resources are indeed a strategic resource for society and ecosystems. By focussing on a mature source of electricity generation, how to minimize its negative ecological impacts and innovate on its role in the ecosystem I am confident that we are moving towards much better management of water as an important public good by learning more on how to make the critically important hydropower sustainable.

- I thank everyone for all their hard work and the very inspiring research papers.

Excursions

Thursday 15. June 2023

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The conference offered excursions to the salmon rivers Surna, Driva, Orkla, Gaula and Nidelva as well as visits to the water power lab at NTNU and the Norwegian Hydro-technical Lab.

Dam rehabilitation at the Follsjø and Gråsjø reservoir (Jon Aarbakk, Statkraft).

Photo: Jo H. Halleraker

Visit to the fish barrier in the National Salmon River Driva, and information about salmon management by project leader Inger Helene Sira (Sunndal municipality).

Photo: Jo H. Halleraker

Conference Chair Jo H. Halleraker and tour guide Kari Anne Kaxrud Wilberg (TrønderEnergy) explaining the Driva hydropower scheme.

Photo: Jakob Granit

Abstracts by author

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Here you can download all the presentations and find additional information about keynote and plenary speakers:

ntnu.edu/sushpconf/presentations

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