Digitalization and real-time control to mitigate environmental impacts of artificial barriers in rivers: Focus on hydropower systems and European priorities

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Digitalization and real-time control to mitigate environmental impacts along rivers: Focus on artificial barriers, hydropower systems and European priorities

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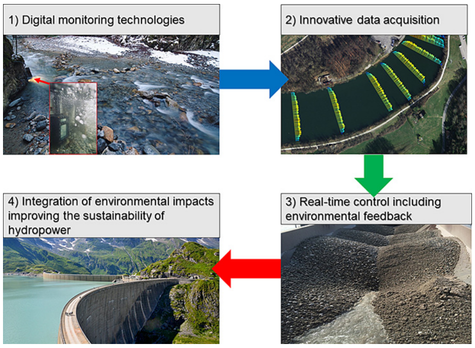
HIGHLIGHTS

- The green and the digital transitions are interconnected issues.
- Digitalization (DICC) is a key strategy to fulfil the targets of this transition.
- DICC in the hydropower sector can provide environmental and energy benefits.
- In Europe, DICC mainly to mitigate hydropeaking, improve water management and fish migration.

GRAPHICAL ABSTRACT



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ABSTRACT

Hydropower globally represents the main source of renewable energy, and provides several benefits, e.g., water storage and flexibility; on the other hand, it may cause significant impacts on the environment. Hence sustainable hydropower needs to achieve a balance between electricity generation, impacts on ecosystems and benefits on society, supporting the achievement of the Green Deal targets. The implementation of digital, information, communication and control (DICC) technologies is emerging as an effective strategy to support such a trade-off, especially in the European Union (EU), fostering both the green and the digital transitions. In this study, we show how DICC can foster the environmental integration of hydropower into the Earth spheres, with focus on the hydrosphere (e.g., on water

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Abbreviations: DO, dissolved oxygen; DICC, Digitalization, Information, Communication and (real-time) Control; EU, European Union EU27; HPP, hydropower plant; O&M, Operation and Maintenance; OGD, open government data; TDG, total dissolved gas; TRL, Technology Readiness Level; WFD, Water Framework Directive.

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quality and quantity, hydropeaking mitigation, environmental flow control), biosphere (e.g., improvement of riparian vegetation, fish habitat and migration), atmosphere (reduction of methane emissions and evaporation from reservoirs), lithosphere (better sediment management, reduction of seepages), and on the anthroposphere (e.g., reduction of pollution associated to combined sewer overflows, chemicals, plastics and microplastics). With reference to the abovementioned Earth spheres, the main DICC applications, case studies, challenges, Technology Readiness Level (TRL), benefits and limitations, and transversal benefits for energy generation and predictive Operation and Maintenance (O&M), are discussed. The priorities for the European Union are highlighted. Although the paper focuses primarily on hydropower, analogous considerations are valid for any artificial barrier, water reservoir and civil structure which interferes with freshwater systems.

Contents

1. Introduction

Hydropower, accounting for 1360 GW of global installed power capacity, and with an electrical generation of 4252 TWh/year in 2021 (International Hydropower Association IHA, 2022), is a multi-benefit renewable energy source. Its flexible operation allows to better integrate the energy output from volatile energy sources (mainly from wind and solar power plants) in the electric grid and provides ancillary services (Bauhofer and Zoglauer, 2021). Hydropower and water reservoirs can provide multiple services, e.g. water storage and flood control, as well as navigation, fisheries, ecosystem services and recreational activities (Branche, 2017). On the other hand, the alteration of fluvial ecosystems and the interruption of the longitudinal connectivity of rivers are relevant impacts caused by artificial barriers (e.g., but not limited to, hydropower ones), with risks imposed on freshwater systems and ecosystems (Nguyen et al., 2018; Geist, 2021; Nielsen and Szabo-Meszaros, 2022). Therefore, sustainable hydropower needs to achieve a good balance between electricity generation, social benefits and impacts on the ecosystem and biodiversity (Rutschmann et al., 2022). This is especially true in the European Union (EU) (Quaranta et al., 2022b).

Hydropower is highly interconnected with all the Earth spheres (hydrosphere, biosphere, lithosphere, atmosphere and anthroposphere) and these are interconnected each other in the so called Water-Energy-Food-Ecosystem (WEFE) nexus, where hydropower systems represent critical nexus points (Dombrowsky and Hensengerth, 2018; Adamovic et al., 2019; Kuriqi et al., 2020; Liu et al., 2022). The hydrosphere and the biosphere are highly interrelated, as any form of life in aquatic ecosystems is affected by the hydrological, chemical and hydraulic characteristics of water bodies, where hydropower plants operate. Hydropower interacts with the lithosphere, trapping sediments and affecting river morphology, that may have considerable and far-reaching ecological consequences on the biosphere. Water reservoirs, including the hydropower ones, interact with the atmosphere, along with local climate behaviour (generating evaporation and, in certain contexts, carbon and methane emissions). Hydropower strongly interacts with the anthroposphere, providing energy and services, but also affecting water quality and quantity. On the other hand, human activities generate pollution (e.g., combined sewer overflows, plastic, chemicals) which affects water quality in reservoirs.

Information and communication technologies (ICT) aimed at real-time control have emerged as a recent and effective strategy to improve the overall performance of hydropower plants. DICC (Digitalization, Information, Communication and Control) can improve operation, efficiency and the environmental performance, thus contributing to the sustainability of hydropower (Cordova et al., 2014; Kougias et al., 2019; Quaranta et al., 2021). DICC can be applied for predictive maintenance purposes, e.g., for extending the equipment lifetime, reducing outages, and assessing cyber-security risks (e.g., Betti et al., 2021). DICC can also improve the overall hydropower plant efficiency, with little or no additional impacts on ecosystems (Kougias et al., 2019; Majumder et al., 2019; Quaranta et al., 2021a). Moreover, DICC can be implemented to increase dam safety (Aswathi et al., 2022) and for landslide prevention (Fellin, 2011; Praveen et al., 2022). Genetic algorithm for real-time regulation can be used for energy and flow forecast (Wardlaw et al., 2005) and in multi-purpose reservoirs to improve water allocation and the economy of the reservoir (Olofintoye et al., 2016). DICC has been extensively explored in the energy context (e.g., efficiency and predictive maintenance improvement), and a brief list of quantitative case studies is reported in Appendix 1.

In the environmental context, DICC allows for the monitoring of biophysical parameters directly related to hydropower operation, including for example water quality and water levels (water level control is the most widely studied DICC application, see Appendix 2), combined with the regulation of power plant components (e.g., turbines, weirs). Furthermore, by monitoring hydropower operation in real-time, changes in these parameters can be directly observed, and their adjustment can contribute to the achievement of the environmental objectives, especially the good ecological potential of rivers (Smith et al., 2007; Jager and Smith, 2008; Moreira et al., 2020). However, a major gap remains in the systematic evaluation of how and to what extent it can improve the environmental performance of hydropower operations. The existing body of literature remains limited and fragmented, despite its rapidly growing relevance. To-date, most of the scientific literature within this context deals with long-term monitoring campaigns to assess the efficacy of implemented measures, with little or no reference to their real-time adjustment and control (Nielsen and Szabo-Meszaros, 2022).

In this review, we discuss the benefits that DICC can entail on the environment. Research gaps for future researches are also outlined, as well as how DICC might balance the trade-off between the competing goals of energy generation and mitigation of environmental impacts. The maturity of the technologies (TRL, Appendix 3) were analyzed together with their technical challenges and knowledge gaps relevant to their further development. Since this study was coordinated by the Joint Research Centre of the European Commission in the context of the Green Deal, Sustainable Taxonomy and the EU Horizon call on hydropower digital solutions,[1] final remarks were provided with direct applicability to the European context, although references from all over the world were considered. The following main areas have been identified for DICC implementation and are described in the following sections:

- ❖ Hydrosphere and biosphere
- Water quality: oxygen, pollutants from the anthroposphere, temperature, oil spills
- Water quantity: control of ecological and environmental flow, withdrawals and releases
- Water temporal distribution: hydropeaking
- River continuity: upstream and downstream fish passage facilities
- ❖ Lithosphere
- Sediment management
- Seepage and leakages
- ❖ Atmosphere
- Methane and Carbon emissions
- Evaporation from reservoirs

2. Hydrosphere and biosphere

2.1. Water quality

Water quality is essential to support aquatic life, biodiversity and to provide resources to the human activities. Human activities, including hydropower, may impact the water quality (Peters et al., 2006). In the following sections, the DICC aimed at improving water quality is discussed in relation to dissolved oxygen, water temperature and ice, chemical and biological pollutants, and oil spills (Fig. 1).

2.1.1. Dissolved oxygen

Depending on the location and characteristics of dams and reservoirs (e.g. alpine reservoir vs. run-of-the river), the decomposition of inundated vegetation and organic matter may induce periods of low dissolved oxygen (DO) levels or anoxia. This situation may continue until a stable state is reached, which may take decades. There is a risk when water is taken from deeper zones of hydropower reservoirs, and discharged downstream, as it may have a low concentration of DO (Pleizier et al., 2020) as a result of either aforementioned decomposition process, or seasonal eutrophication processes due to thermal stratification. The oxygen level can drop under the minimum limit of 5–6 mg/L, needed for aquatic life, e.g. 3 mg/L for survival of trout and 4 mg/L for sensitive cold-water invertebrates (Bunea et al., 2010). Low DO concentration can affect both aquatic life in the reservoir and migratory fish in the river reach downstream the dam. On the other hand, super-saturation can also be risky. DO concentration can be used as a proxy for determining Total dissolved gas (TDG) (Nielsen and Szabo-Meszaros, 2022) and when the water becomes supersaturated (Weitkamp and Katz, 1980; Pulg et al., 2020). Water is commonly considered supersaturated when TDG level exceeds 110 % (for shallow water) or a higher value, i.e. 110 % plus 10 percentage points for any meter of water depth (for example, 120 % at 1 m depth, 130 % at 2 m depth in the receiving water body) (Pleizier et al., 2020). Supersaturation may happen under episodic conditions related to hydropower production (e.g., air admission to turbines, or air entrainments from secondary intakes at high-head hydropower systems). When supersaturated water is released and transported downstream, it can be harmful to aquatic life. Fish are barely exposed to supersaturated water in nature, therefore their resistance level to high TDG levels is low. The effect of supersaturation is gas bubble diseases in fish when gas bubbles develop and accumulate in their tissues (Weitkamp and Katz, 1980). The disease may lead to increased mortality, and extreme high TDG levels can wipe out fish completely over kilometers downstream of the hydropower plant.

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[1] https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/topic-details/horizon-cl5-2022-d3-03-08.

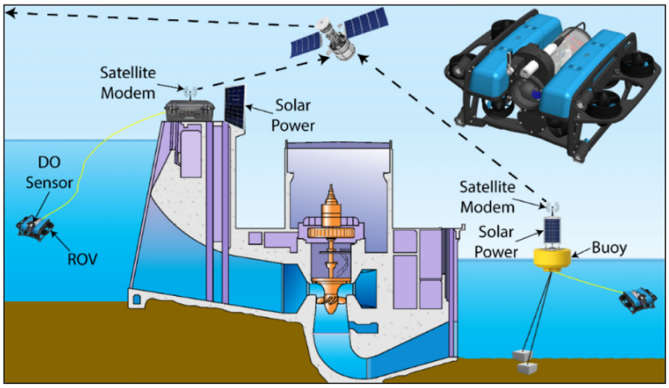

Fig. 1. Visualization of a real-time and autonomous water quality monitoring system (ROV) in operation (Source: Nielsen and Szabo-Meszaros, 2022).

At hydropower plants where supersaturation or DO deficit happen, rapid detection via loggers downstream is essential to mitigate the effect on the environment, where their prevention is not possible, e.g., by a tailrace channel or a retention basin below the turbines. DO levels can be monitored (e.g., by the remotely operated vehicle described in Salalila et al., 2020), and the power plant operation can be adjusted accordingly to mitigate impacts. Oxygen concentration in the water released downstream can be adjusted by implementing operational techniques, e.g. using multiple level intakes for hydropower production, spilling or sluicing water from the near-surface zones, fluctuating the timing and duration of flow releases, increasing residual flows, and flow mixing. Operational measures are also effective to mitigate or prevent release of flow with high TDG levels (Nielsen and Szabo-Meszaros, 2022). An additional measure is to release oxygenated surface water during low DO periods or during critical life history stages of aquatic species (e.g., fish spawning or recruitment). In some cases, small adjustments in reservoir storage rates or water release schedules can have significant ecological benefits (Peterson et al., 2003). Auto-venting turbines and self-aerated draft tubes can be used to mitigate low DO. In auto-venting turbines the air is usually drawn through the turbine runner, whereas in self-aerated draft tubes the air is injected through a dedicated section of the draft tube. Self-aerated draft tubes use a real-time control system that controls the amount of air injected in the water column as a function of real-time measurements of the oxygen concentration and the pressure in the draft tube. The aerated draft tube has been tested on a small Francis turbine of 318 kW (Bucur et al., 2019; Bunea et al., 2021). The TRL can be considered 8–9, but this technology has not been extensively used yet. Self-aerated draft tubes needs to be tested on turbines of larger sizes (in the range of those installed in deep hydropower reservoirs).

2.1.2. Water temperature and ice

River temperature noticeably affects ecosystems, e.g. biochemical metabolism, reproductive success and mortality (Feng et al., 2018; Bui et al., 2018). Hydropower operation may affect water temperature, especially with the thermopeaking effects in reservoir power plants.

In order to meet peak demands for electricity, storage hydropower plants produce flexible electricity, which results in an intermittent release of flow that takes place mostly at daily and sub-daily frequencies (Moreira et al., 2019). This process is called “hydropeaking” (see Section 3). Hydropeaking may also significantly affect the thermal regime of rivers. Indeed, especially in mountain areas, releases from high-elevation reservoirs are often characterized by a different temperature from that of the receiving body, thus causing sharp water temperature variations named ‘thermopeaking’ (e.g., Dickson et al., 2012). Reservoir operation with hypolimnetic release may result in the release of colder water in summer and hotter water in winter from deeper zones of a reservoir, which may therefore paradoxically contribute to the survival of cold water stenotherm fish species, such as salmon during their summer migration period (Feng et al., 2018). Zolezzi et al. (2011) calculated that a hydropower plant (HPP) in Noce river (Northern Italy) generated warm thermopeaking from September to January and resulted in additional (up to 4 °C) heating with respect to that associated with the natural daily fluctuations. On the contrary, cold thermopeaking occurred from March to July and cooled down the temperature (up to 6 °C), in contrast with the natural trend that would result in heating during the day. Carolli et al. (2008) calculated that temperature increased up to 4.5 °C during autumn and winter, whereas decreased up to 5.9 °C during spring and summer, in Noce river, Italy.

Recent technological DICC advances have enabled higher resolution GSM/satellite and cellular-based options for monitoring water temperature, light and chemical data in rivers and reservoirs (Heggenes et al., 2021; Vyshnevskyi, 2020; Pacheco et al., 2015). For example, in Pacheco et al. (2015), the SIMA system (a set of hardware and software developed for data acquisition and real-time monitoring of hydrological systems) was implemented to acquire surface data of temperature, conductivity, pH and oxygen.

By monitoring in real-time the water temperature of a reservoir, it is possible to activate mixing or selective withdrawal mechanisms to reduce impacts downstream. Water may be mixed in reservoirs (destratification) to minimize thermal stratification in deeper/large dam reservoirs with only bottom intakes, especially in tropical and lowland reservoirs. Bubble plumes create artificial circulation within the reservoir, and pumps can pump water from the surface to the bottom intake. Submerged curtains can guide surface water to the intake, or prevent cold deep water from entering the hydropower intakes. Flexible or multiple water release from reservoirs (selective withdrawal, with withdrawal structures at different vertical locations, Saadatpour et al., 2021) is the most effective way for controlling the water temperature of reservoir releases. In the hydropower dam on the Alta River, Norway, a secondary upper intake was intended for both summer and winter temperature control releases. This measure theoretically lowered temperatures near pre-regulation conditions, but also reduced annual discharge and hydropower production (Heggenes et al., 2021). Saadatpour et al. (2021) reviewed the most representative scientific studies on this topic and should be referred for more details.

Also ice may be a problem, especially at high altitudes and latitudes. Yapa and Shen (1984) showed that the average power loss per winter at Moses-Sounders Power Dam was 49,180 MWh, which is equivalent to 82,131 barrels of oil or 2.46 million US dollars. A study in Swedish hydropower intakes in the early 1990s estimated annual income losses of $1 million to $2 million due to frazil clogging of intakes. Annual operations and maintenance costs at the U.S. Corps of Engineers projects due to ice problems were estimated as $33 million in 1992. Furthermore, thermal ice pressure on the dam can reach 250 kN/m, while the ratio of the volume of immobilized water to that of the active storage can reach 20 %. Such reductions in active storage due to ice may result in loss of peak power value for power companies during winter. Extra head losses caused by clogging of trash racks due to frazil ice can reach 10 % of the gross head (Gebre et al., 2013). Operational tools for ice mitigation require both the testing and development of modelling tools, but also an increased effort in acquiring real-time data for verifying the models and for operational use. Historical and real-time data on ice conditions are essential for the calibration of the models to be implemented in mitigation measures, e.g.: selecting withdrawals, heating of gates and trash racks, timely removal of frazil ice and ice floes from water conduits, and drainage of emptied tunnels and conduits (Gebre et al., 2013).

2.1.3. Chemical and biological pollutants

Thousands of chemicals encompassing different classes of substances such as pesticides, pharmaceuticals, personal care and industrial products are discharged into the water environment from agricultural areas, urban settlements and industrial sites. These chemicals may harm aquatic ecosystems and human health even when single substances occur at very low concentrations (ng and pg/L range) (Gómez et al., 2021). This represents a clear interaction between the anthroposphere, the hydrosphere and biosphere. Pollutants can also include plastic (both macro, e.g. bottles, and microplastic), wastewater substances reversed in rivers during combined sewer overflows, and other chemical substances and nutrients, like Nitrogen (e.g., from agricultural runoff) and Phosphorous (e.g. from detergents). Also hydrophobic substances may be present in reservoirs: Lindim et al. (2016) indicate that the top ten emitted pharmaceuticals in their study set of 54 substances are all emitted in amounts above 0.5 ton/y to both surface waters and soils. Perfluorinated compounds (PFAS) can also be found in sediments (Schaanning et al., 2020). In the following paragraphs, three pollutants are discussed: plastic, wastewater and chemicals/ nutrients.

Most of the plastic discharged into the oceans comes from rivers. However, rivers have been found to behave like a plastic reservoir (van Emmerik et al., 2022), and this behaviour may be also due to the large presence of barriers, especially in the EU. Trash racks of hydropower dams can help in trapping, and removing from water, macroplastics and microplastics trapped in sediments (e.g., at HPP Kirchbichl annually 2455 m^3 debris (mean value 2003–2015) is removed at the trash rack) (Watkins et al., 2019; Liedermann et al., 2018). In the Austrian stretch of the Danube River (349 km), there are 11 hydropower plants in which litter is retained. At all sites, waste is separated at the intake structure to prevent the turbine from damage. The total amount of waste which is removed from the intake structures of all hydropower plants along the Austrian stretch of the Danube River amounts to an annual average of 7500 t (tons) per year. Considering that 2 % are estimated to be made of plastic, approximately 150 t of plastics are removed from the river annually as a rough guess (González et al., 2016). Every year, around 290 t of macroplastics are disposed of by operators of hydroelectric power plants from running waters in the Danube basin. Most of this is packaging waste such as plastic bottles. Waste from the agricultural sector, such as foil and plant pots, as well as construction waste such as polystyrene, is also removed from the river network.[2] DICC, by means of camera systems, could be implemented to detect such plastic and avoid mixing with natural sediments, that may also trap microplastic (Watkins et al., 2019).

Rivers often receive effluents from wastewater treatment plants, e.g. in urban areas (Hülsmann et al., 2021), or from combined sewer overflows (CSOs). The total amount of CSOs in the European Union was estimated to be as equal as 5782 million m^3 per year (Quaranta et al., 2022a). Increasing discharges downstream of reservoirs is a widespread management practice in central Europe where reservoirs are used to keep the discharge in downstream rivers above a critical level in order to provide the river ecosystems with a certain dilution potential. The flow increase is done by operating on upstream hydropower intakes in real-time. In mountainous regions, 10 % to 20 % of sewer system installations are located at sites having the potential for implementation of this measure (Achleitner and Rauch, 2007). Shin et al. (2022) emphasized that the real-time monitoring of treated wastewater and hydropower effluent should be implemented to avoid water quality incidents related to the transport and dispersion of harmful cyanobacterial blooms and geosmin in the environment.

The implementation of multi-objective models for optimal operation of the reservoir can also help in mitigating the adverse impacts of chemicals, for example by proper water releases and withdrawals to dilute and prevent polluting events, respectively, supported by DICC. In Ferreira and Teegavarapu (2012), Nitrogen and Phosphorous were adopted as objectives and constraints for a reservoir in Brazil (other water quality parameters could be introduced to address case-specific problems where other pollutants are of concern). The temporal scale for optimization was limited to 1 day. Shorter time intervals for optimal operation can be considered for real-time unit scheduling, especially for run-of-the-river systems under variable inflows.

2.1.4. Oil spills

Hydraulic turbines generally use pressurized oil to lubricate the turbine bearings and the sliding components of the hub. However, incidental oil leakage from hydraulic turbines can generate negative impacts on the environment, as well as may cause operational and maintenance problems (St. Germain, 2018). According to estimates reported in Quaranta (2023), the lubricant oil consumption in the whole European hydropower fleet was estimated to be 22×10^3 t/year. The share of losses due to cleaning, evaporation, foam formation, leakage through the oil system and through the seals, when sampling for analysis, may be approximately 59 % (although not all of this may be lost into the environment).

In most hydropower plants oil leakages are not monitored, but rather they are detected by periodic visual inspections. In the future, with the rapid development of cloud computing, big data, Internet of Things, and artificial intelligence technologies, the operation and management of hydropower stations will develop in the direction of interconnection, data mining, and intelligent decision-making. Therefore, in addition to the visual inspection, future measures to deal with oil mist will be closely combined with the control and governance of bearing oil mist leakage based on a smart power station, diagnosis and prediction of bearing oil mist leakage built on artificial intelligence (AI), and guidance and solutions of bearing oil mist leakage acquired from cloud services (Sun et al., 2022). The real-time monitoring of oil pressure could reveal anomalous leakages and thus asking for emergency maintenance and checkup (Betti et al., 2021; Wang et al., 2021; Bently Nevada, 2022).

2.2. Control of ecological and environmental flow, withdrawals and releases

Flow monitoring at hydropower dams and weirs (e.g., river flow upstream of the dam, withdrawn discharges, release from spillways) can provide adequate knowledge and control on the entity of water withdrawals/ releases in relation to the effective incoming river flow, and, therefore, on the compliance to key water licence terms (e.g. maximum discharge withdrawn, mandatory downstream releases, environmental and ecological flows). Monitoring incoming and released discharges can also be used as a tool to safeguard downstream river ecosystems, since it allows to quantify the effective impact upon the aquatic ecosystems in terms of reduced habitat availability in the different periods of the life-cycle of the interested species and, when needed, to activate adequate specific mitigation measures by regulating the flow to be released by appropriate manoeuvring systems of intake gates (Vezza et al., 2014; Parasiewicz, 2007; Parasiewicz, 2008; Water Framework Directive, 2014). Government agencies within the EU already collect and share open government data (OGD) for national and regional monitoring, but the main tasks for real-time technologies are to aggregate this data, and post-process into the corresponding recommendations. There are many countries that have real-time information online (e.g. Austria - Tyrol,[3] France,[4] Germany - Bavaria,[5] Slovenia[6]), and that could be used by hydropower operators.

The ecological flow is defined by the Water Framework Directive (WFD) as an hydrological regime consistent with the achievement of the environmental objectives of the WFD in natural surface water bodies as mentioned in Article 4(1) (Directive, 2014, CIS 31). Ecological flow takes into account preferences of and for aquatic species, while the environmental flow (Eflow) aims to mimic abiotic natural processes in addition to fish preferences, i.e., sedimentation, continuity. Proper definition, modelling and efficient implementation of Eflow require a significant amount of hydrological data derived from the monitoring of the hydrological regime, often integrated by hydrological models where the time series of measured data is of limited duration (Water Framework Directive, 2014). The available methodologies for estimating Eflows are: (1) Hydrological, (2) Hydraulic-Habitat (e.g., MesoHabsim, CASiMiR, better detailed in Appendix 4), and (3) Holistic methodologies. After EFlow modeling, it is required to monitor and control it to comply with specific prescribed release modulation

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[2] https://www.cleanenergywire.org/news/hydropower-plants-help-remove-plastic-waste-water-bodies-study.

[3] https://wiski.tirol.gv.at/hydro/.

[4] https://www.vigicrues.gouv.fr/.

[5] https://www.hnd.bayern.de/pegel/meldestufen.

[6] https://www.arso.gov.si/en/water/data/stanje_voda.html.

scenarios (e.g. downstream release defined as a real-time % of the river discharge[7]).

For instance, in Aosta Valley Region (NW Italy), renewal and release of water licenses are analyzed by the competent authorities and stakeholders within a decision-making process based on a multi-criteria analysis (MCA) procedure to identify the most sustainable downstream release scenario. The scenario includes real-time release alternatives, that foresee, for each month, a basic flow value to be left in the river downstream of the dam, incremented by an additional release quantified in real-time, varying on hourly basis, calculated as a percentage of the flow rate measured upstream of the dam (Vassoney et al., 2019, 2020, 2021).

At the Graines HP plant a continuous monitoring system installed at the dam measures the incoming river flow every 5 min and, through a programmable logic controller (PLC), the opening or closing of the gates is regulated to adjust the downstream release to the prescribed scenario (baseline discharge and additional flow ranging from 12.5 to 30 % of the incoming flow). Such real-time management of the downstream releases can be more easily implemented by new or recently built plants, where gates and electromechanical components can be regulated by PLC.

Tallinn University of Technology has built and deployed a web application demonstration of an automated environmental flows system, based on open river monitoring data, typically collected by national authorities.

The modelling process has 4 steps:

1. Hydrological open data collection and pre-processing (imputation, correction of faulty data).
2. Configuration of sub-models for dynamic discharges (e.g. hydropower plant operations, irrigation abstraction, drainage re-routing or industrial water discharges).
3. Using previous time series, and knowledge of plant operations (e.g. water abstraction for hydropower); machine learning models are trained to forecast future flow rates at user-defined locations.
4. Eflow prediction, including uncertainty bounds. The methods used to assess environmental flows can range from a fixed percentage of the mean annual flow, to highly complex evaluations including fish habitat suitability, its availability and physiochemical water quality.

The proposed system adds value to existing environmental monitoring data, reduces development and operational costs, facilitates streamlining of environmental compliance and allows for any authority with similar data to reuse or scale it with new data and methods. The TRL of this technology is between 5 and 6, as it has been created, tested and validated at an Estonian Eflow web application. It is fully automated and makes use of the available 54 river monitoring stations in the Estonian national hydrological monitoring system (Miasayedava et al., 2022). Costs to setup this software system for other monitoring sites range from 150,000 to 500,000 EUR per installation. The cost depends on the number of submodels needed to be developed, trained, tested and validated for individual hydropower plants and other sites which drive dynamic changes in the discharge and/or temperature regime of a river. Annual operating costs are estimated to be 50,000–100,000 EUR, depending on the level of integration required with the OGD data provider and the means in which the Eflow data are exported (e.g. text file, interactive map, real-time predictive model results with estimated Eflow uncertainty bounds). In the current implementation, the Eflow model requires previous datasets of a time duration of a minimum 20-year time frame for statistical / machine learning estimation of low-flow scenarios. Sites for which short-term datasets are available (e.g. 5 years or less) would need to be coupled with a long-term hydrological model. Code for running the Eflow web application is openly available and includes documentation on setup, installation and augmentation.[8] Additional online IoT (Internet of Things) sensors in rivers, upstream and downstream of hydropower sites, can be integrated to develop data-driven models with higher temporal resolution.

A demonstration web application was created for real-time Eflow estimation based on Estonian hydrological OGD. This data is publicly available from the Estonian national hydrological sensing network.[9] The cost of developing the system was EUR 50,000, as it included only sub-models for individual gauging station sites with time-series longer than 20 years.

2.3. Hydropeaking

Hydropeaking is the discontinuous release of water to accommodate peaks of energy demand. Hydropeaking causes artificial flow and water level fluctuations downstream of the dam, that can cause damages to the aquatic life, riparian vegetation and river morphology (Greimel et al., 2018; Moreira et al., 2019). In critical periods (e.g. for larvae and juvenile grayling) down-ramping rates higher than 12 cm/h (Auer et al., 2017), as well as up-ramping rates higher than 15 cm/h, are typically deemed critical (Schmutz et al., 2015). Salmaso et al. (2021) selected 26 papers regarding the monitoring of the effects of hydropeaking on benthic macroinvertebrates (among which 16 were conducted in European watercourses), and showed that biomass reduction can reach 95 %. Hydropeaking mitigation measures can be ranked as follows: (1) hydropeaking diversion hydropower plants, (2) retention/compensation basins and (3) operative measures (Greimel et al., 2017). In this section we discuss how these measures can be implemented to control and mitigate hydropeaking impacts in real-time.

2.3.1. Diversion systems

Hydropeaking diversion HPPs divert water to a larger catchment downstream (Reindl et al., 2022). The largest plant of this type is the HPP GKI (Herdina, 2018; Moreira et al., 2020; Kopecki et al., 2022), which started operation in November 2022 in the alpine region of Tyrol, in Austria. Moreira et al. (2020) simulated the operation of the proposed compensation basin as well as the associated diversion waterways and hydropower plant with a 15-min resolution, showing the possibility of combining different mitigation measures in integrative hydropeaking mitigation approaches. Kopecki et al. (2022) showed that the number of events in which the down-ramping rate or the base to peak flow ratio exceed critical thresholds can be reduced by 2 orders of magnitude (on an annual basis) or even eliminated with an adequate plant operation.

2.3.2. Compensation basins

Compensation basins are a promising hydropeaking mitigation measure, as they can have a no, or even positive, impact on the hydropower plant revenues (the discharged flow rate can be scheduled with higher flexibility), differently from operative measures (i.e. the implementation of ramp rate constraints in the hydropower generation schedule), that instead may have a relevant impact on hydropower plant production. Compensation basins can also entail ecological improvements (Tonolla et al., 2017). Quaranta et al. (2020) described the case study St. Anton in the Province of Bolzano (Italy), at river Talfer, where a compensation basin was built as a cavern with a volume of approximately 95,000 m^3. It both mitigated hydropeaking and increased the available habitat area by 67 %. Furthermore, the maximum flow rate was increased from 15 to 18 m^3/s and the maximum power generation from 72 MW to 90 MW. The older retention basins were not built for hydropeaking mitigation, but in order to smooth down the flow conditions for other hydropower plants in the tailwater (Reindl et al., 2022). To the best of the authors' knowledge, the first compensation basin built in Europe for hydropeaking mitigation is located at the Innertkirchen hydropower plant (Switzerland), with a volume of 80,000 m^3 (basin + tunnel). Currently, in Austria, the retention basin

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[7] In some cases, for new licenses of significant water withdrawals, a real-time modulation of releases could be prescribed by the competent Authorities: e.g. Regione Piemonte (DPGR 8/R/2007 Annex C) for sites with $Q_{withdrawn} > Q_{120}$ requested that $Q_{released} = MVF + x(Q_{upstream} - MVF)$, with x to be defined during the water licence issue as a value between 0.1 and 0.2, MVF = base minimum vital flow; $Q_{upstream}$ = incoming river discharge. Compliance to the above potential prescription obviously requires a real-time monitoring of the incoming and released discharges.

[8] https://github.com/effie-ms/eeflows.

[9] https://www.ilmateenistus.ee/siseveed/ajaloolised-vaatlusandmed/.

Silz with a volume of 300,000 m^3 is under construction and will start operation in 2024 (Reindl et al., 2022).

In order to be effective and to optimize their size (and cost), a suitable real-time control system is necessary to operate the regulation devices (gates, valves, etc.) of the water outlet (and in some cases inlet). Some case studies have been analyzed in Pérez-Díaz et al. (2012) , Bieri et al. (2016), Premstaller et al. (2017), Pisaturo (2017), Popa et al. (2019) and Dorfmann and Seidl (2021). The compensation basin at the Innertkirchen hydropower plant was tested between autumn 2015 and spring 2016. The steps taken for the design of the compensation basin are summarized in several articles (Bieri et al., 2014; Person et al., 2014; Tonolla et al., 2017). Müller et al. (2016) provided a brief description of how various gates located both at the inlet and outlet of the compensation basin are operated so as to control the basin outflow to the river. The implemented control system uses as input the forecast discharge release in the compensation basin along with real-time measurements collected by several water level sensors. In the Austrian region of Tyrol, a hydropeaking mitigation measure along the upper Inn river is foreseen, which combines buffer reservoirs, diversion hydropower plants and retention basins (Reindl et al., 2022), and increased hydropower production.

2.3.3. Models to forecast scenarios and operative measures

Operative measures implement ramp rate constraints in the hydropower generation schedule, in order to limit hydropeaking impacts on riparian vegetation and aquatic organisms, such as macroinvertebrates (Leitner et al., 2017; Farhadi et al., 2022) and fish (Almeida et al., 2017; Capra et al., 2017; Kopecki et al., 2022). Salmaso et al. (2021) showed that biomass recovery can range from 15 % to 60 % after implementing such mitigation measures (e.g., increased base flows and reduced peak flows).

In order to implement well these measures, models have been developed to quantitatively link key hydrological parameters, altered by hydropeaking (such as duration, frequency, rate of change, magnitude of the inundation), to key biological parameters of certain riparian plant species, and to forecast scenarios. These models show the response of vegetation and the thresholds from which the impact of hydropeaking on vegetation is irreversible. Although the models need to be developed in advance, once they are available, operators can rely on them for optimizing flow releases to enhance riparian areas, also in real-time. Such a modelling approach has been tested on the operation of several hydropower plants along the Ume River in Northern Sweden to enhance its riverine zones. The model and the associated quantitative data can be consulted in Bejarano et al. (2020). Key results indicate that deeper and more frequent inundations hampered plant growth, decreased survival and germination rates and increased drag rates of transplants, especially for small seedlings. The mean rise rate of the water-level fluctuations was only relevant for the germination, which was disfavoured by rapid changes in water levels. The germination, survival, and drag rates of transplants were the variables most responsive to hydropeaking.

CASiMiR, already discussed in Appendix 4, includes a Hydropeaking-section, which is a model able to process unsteady flow data for habitat risk assessment. Dynamic parameters as ramping rates (water level changes over time) are used to assess the stranding risk or drift risk for young fish during rapidly changing flows that occur in rivers under hydropeaking impact. Additionally, the *habitat persistence*, an indicator for the sustainability of habitats for organisms with restricted mobility (larvae, macroinvertebrates), can be quantified and assessed for different scenarios of turbine operation and morphological mitigation.

The main challenges are difficulties in model development (which is complex and time-consuming) and the limitations in the extrapolation to other rivers beyond those in which models were developed. These models are a reliable solution for an effective operation, to be implemented in real time, of power plants causing hydropeaking.

2.4. River continuity: upstream and downstream fish passage facilities

Fish passes, or fishways, are hydraulic structures designed to allow fish migration through an obstacle, such as a dam or a barrier (Schletterer et al., 2016). Fishways are very sensitive structures due to the needed equilibrium between biological and hydraulic aspects inside and around them and, thus, their efficiency is often far from acceptable (Bunt et al., 2012). In this sense, the variability of flows at hydropower-regulated sites modifies the hydraulic conditions within the fishway, affecting biological response of migratory fish and, in the worst case, deviating from their principal objective, i.e., to allow the free movement of fish across and obstacle (Fuentes-Pérez et al., 2018). Despite the possible consequences of hydrological variability within a fish pass (DWA, 2016), the effects are sometimes not considered during their design and assessment phase (Fuentes-Pérez et al., 2016; Fuentes-Pérez et al., 2017). Moreover, the effect of hydraulic alterations on the efficiency of a fish pass has to be taken into account for management purposes (i.e. hydraulic conditions control, attraction flows, clogging detection, etc.) (ÖWAV, 2020).

DICC has been recently introduced to improve the efficiency of fish passes, combining several strategies: water level sensors can be used to continuously verify the hydrodynamic condition within the fish pass and to activate gates and other hydraulic structures to adjust them to more adequate levels when needed (e.g., see the section *Bypasses with variable flowrates*). Camera/video-based monitoring of passages of migrating fish may help in understanding the efficacy of the control system implemented at the fish pass, and allows the timely activation of particular measures (e.g., gates, turbine shutdown, increase of the attraction flow at the fish pass entrance, etc.) depending on the presence and distribution of fish approaching/accessing the fish pass. Statistical models could be used when video monitoring is not possible, although governmental monitoring requests often require of abiotic and biotic measurements. Telemetric biosensors can also be used to monitor fish movements. Based on the above-mentioned innovative sensor systems, increased attraction flow at fish passes for upstream migration or downstream bypasses with variable flowrates and/or turbine shutdown can be activated and operated in real-time for facilitating upstream or downstream fish migration, when the initial stages of the migratory event are detected. In this section, three main applications are discussed: the tool *Smart Fishways* as hydraulic sensor system to improve the hydrodynamic characteristics inside fish passes, bypasses with variable flowrates and turbines shutdown. Video/camera monitoring, telemetric biosensors and statistical models to support the operation of these applications are also described.

2.4.1. Smart Fishways

Smart Fishways is an interdisciplinary framework and toolbox that combines fish biology, fishway hydraulics and networks of sensors. The aims of this tool are: to monitor fishway performance in real-time considering multiple environmental conditions, to identify key components affecting fish passage and the optimal layouts to facilitate the passage, to set adaptive management rules, and considering these management rules to adapt fishways to hydrological and climatic uncertainty. The sensor networks (water level nodes, environmental variable node, and fish counter node) serve as a non-invasive linkage between biology and hydraulics. Sensors provide real-time information to optimize the performance of fishways (that is assessed autonomously by knowledge and statistical models). The general technology readiness levels (TRL) of *Smart Fishways* is 7, and some of the technological components of the framework (e.g. water level and environmental variable nodes) are at TRL 9. Part of the individual sensors of the system are already market ready and commercialized. Potential applications of *Smart Fishways* include fish passage solutions and river remote monitoring, fishway performance assessment (hydraulic and biotic) or their remote adaptive management. Likewise, developed sensor networks can be easily adapted to other fields of river engineering and environmental monitoring (Fig. 2). Appendix 5 describes two case studies with related equipment.

The *Smart Fishway* framework is developed under open hardware and software technology with a modular design principle to be easily adaptable to different scenarios; therefore, the cost is being optimized to make its usage affordable in any region. The preliminary market price estimation of a full working system installed on a fishway installed at obstacles of 2–4 m height is around 15,000 € (including on-side calibration and data

Fig. 2. *Smart Fishways* sensors implemented in a fish pass.

management strategy). It is expected that future optimizations will reduce the cost. The main challenge of *Smart Fishways* is to develop consistent models able to optimize fishway performance for multiple target fish species. The system is currently installed in three fully operational study cases in the Spanish Duero River basin, and in two sensor networks in Portugal (for the project EcoPeak4Fish). By now, data are being used to assess the hydraulic performance of the fishway, using trained neural-networks that compare the measured water-level variables with expected hydraulic performances, to detect anomalies and trigger management alarms (Fuentes-Pérez et al., 2021). The next step is to detect hydraulic scenarios that maximize the fish passage and to trigger operational alarms in the associated hydropower plants. This can be achieved by modelling fish movement with variables measured by the sensor network (environmental variables and hydraulic variables) and afterwards using real-time variables as model inputs (see García-Vega et al. 2018 and 2022).

Quantitative data will be available from the end of 2023. However, a previous study, that included an analysis of 64 stepped fishways of different types (50 % of whole existing stepped fishways in Duero basin), concluded that the 32.8 % of studied fishways presented problems due to a lack of maintenance (Valbuena-Castro et al., 2020). In this context, the Smart Fishways system potentially has a direct and positive impact in several fishways, without considering the adaptive management possibilities or the economic benefits of scheduling in real-time fishway maintenance. In the same way, the transmitted real-time information avoids or reduces the control visits by river authorities and operators to check Eflows, and related costs, providing an additional economic benefit. With regards to adaptive management, previsions are case and year-dependent. For instance, models in a study case (Tormes River, Duero River basin) suggest that establishing adaptive management, with the collected environmental variables and using random forest modelling, could provide an increase of the passage efficiency in the range of 10 % to 720 %, depending on the weather conditions of a specific year (García-Vega et al., 2022).

2.4.2. Bypasses with variable flowrates

Bypasses are hydraulic structures to allow the downstream fish migration. Bypasses for facilitating downstream migration of fish operating with variable flowrates depending on tailwater conditions are also under development. Among these, there are partially-filled pipes discharging into the downstream or upstream receiving water and that change configuration as a function of the tailwater conditions. This technology can benefit from DICC in order to minimize the risk of injury and mortality. The system is easy to implement, as the upstream and downstream water levels determine the DICC control law. Two case studies were analyzed in Austria, one for upstream (fish lift Runserau, see Thonhauser et al., 2017) and one for downstream (at the HPP Kirchbichl) migration. Live fish and passive sensors have been tested in partly filled bypass pipes, which revealed that both bypasses have no reasonable risk of fish injury or mortality at the test sites (Tuhtan et al., 2018; Wagner et al., 2022). However, planning for a site-specific adjustment of flows based on head and tailwater conditions requires considerably more engineering effort, as multiple hydrological conditions must be modelled and accounted for. Once operational, bypasses with variable flowrates require additional electromechanical equipment for the monitoring of flows or water levels. Due to sparse literature on the risk of injury and mortality to multiple freshwater fish species and life stages at bypasses, the designs should be highly conservative (e.g. minimum water depth in the partly filled pipe should be 0.23 m (WDFW, 2000) in the receiving pool, and the water depth should be deeper than ¼ of the fall height (DWA, 2005)). Depending on the site-specific physical conditions, carrying out tests of the physical conditions during bypass passage may be highly challenging using passive sensors or live fish. Consideration of how such tests and monitoring campaigns could be performed should be discussed with experienced biologists and engineers as part of the design process, as adding simple mounting points for a net cage, or access ladders can substantially reduce the cost of field work after construction has been completed.

2.4.3. Turbine shutdown

Turbine shutdown is generally operated based on a fixed schedule for downstream migration of diadromous fish, and the decision criteria that are implemented in turbine management strategies are rather simple. For example, the turbine shutdown schedules are commonly based on calendar dates and river flow conditions, which are assumed the primary triggers of eel movements, instead of on the effective migration stages and current migration conditions. Turbine shutdown is generally put in place from nightfall to dawn during the migration period when river discharge or variation in river discharge exceeds given threshold values. Adam and Schwevers (2006) proposed the Migromat ®, where the activity of eels in a tank close to the river is analyzed to predict migration events of free-living eels, as an early-warning system for the detection of the downstream migration. Several case studies across Europe analyse the downstream migration of diadromous fish (e.g. Økland et al. 2017). Analytical tools are still lacking to define robust and optimal threshold values for the decision criteria based on the monitoring data collected at hydropower plants (Teichert et al., 2020). In Tétard et al. (2021), at the Poutès dam (Allier River, France), turbine modulation and/or shutdown during the night, and reservoir level lowering, were implemented. Level lowering significantly reduced the median passage time of fish over the regulated site from 3.4 days to 4.4 h. However, even with high spill during turbine modulation, the risk of smolt being drawn towards the turbines was increased at low reservoir level due to the site configuration, greater proximity to the surface and weak repulsive effect of the rack. Several smolts could migrate during daytime and twilight during floods, even at the beginning of the migration period.

Targeted turbine shutdown has potential to protect smolts, but implementation requires studies taking into account of the specific characteristics of the site and a flexible approach. Furthermore, shutdowns of turbines may cause the accumulation of fish inside the draft tube, mainly in rivers with a high amount of fish (Schilt, 2007). Hydro-acoustic systems operated in real-time may help the monitoring of ichthyofauna confined in draft tubes and to operate real-time maneuvers (da Silva et al., 2021).

In any case, combining the turbines shutdown with real-time video monitoring systems (see *Video monitoring* section) aimed at detecting the initial stages of the migratory event or to statistical models aimed at predicting the fish migration timing based on monitored environmental variables (see *Statistical models and telemetric biosensors* section) has the potential to increase the effectiveness of this mitigation measure and to significantly reduce the costs (production losses) related to a fixed shutdown schedule.

On the other hand, accidental turbine shutdown, with abrupt stop in flow, may result in stranding of riverine biota. Bypasses valves, controlled on real-time, may be a solution to mitigate the impacts on biota. Halleraker et al. (2023) estimated that more than 650 Norwegian hydropower plants may need well-operated bypasses valves.

2.4.4. Video monitoring

Real-time monitoring through video recording systems installed at fish passage facilities (up and/or downstream migration routes) are remotely accessible and constitute a relevant source of ecological information, as this date can be integrated with institutional fish monitoring networks (usually based on electrofishing surveys). Video monitoring can allow identifying the starting time of migration periods of the different species (that can vary over years, also due to climate change induced alterations in flow and water temperatures) and, consequently, to operate the HPP in order to facilitate migration. Operative measures include frequent maintenance during spawning periods, activating/increasing attraction flow at fishways entrance, increasing flow releases to maximize available habitat and instream connectivity in the downstream reach, spillways opening or shutdown of the turbines to allow safe downstream passage of target species (e.g., silver eels).

Artificial Intelligence and Deep Learning systems can be used in real-time on the video frames for direct identification of the species. Sonar camera systems to identify fish migration are under investigation by some companies (e.g., EDF (pers. comm. of Claus Till Schneider), TIWAG (Schmidt et al., 2018)). Recent research conducted by a team at the Pacific Northwest National Laboratory, U.S., developed deep learning models to identify migrating eels from imaging sonar data (Zang et al., 2021; Yin et al., 2020). The models employed convolutional neural networks (CNN) to distinguish between images of eels and non-eel objects. The CNN model was first trained and tested on data obtained from a laboratory experiment, which yielded overall accuracies of >98 % for image-based classification. Then, the model was trained and tested on field data that were obtained near the Iroquois Dam located on the St. Lawrence River, U.S.; the accuracy achieved was commensurate with that of human experts. Monitoring the performance of fishways by cameras, and any functional control associated with them, are important operations for several reasons (Soom et al., 2022):

- to verify the efficiency of fishways after they have been commissioned and to adjust their operation if necessary;
- to gather technical and biological information which will be indispensable for the design and development of future fishways (operational feedback);
- to quantify migratory fish populations and describe the pattern of their migration, which is necessary both for the design of any fishway to be constructed upstream on the same watercourse and for rational stock management.

However, the acquisition of suitable underwater cameras is associated with a relatively high initial investment for equipment purchase and installation. The camera system has to be selected based on river type and monitoring purpose. Continuous monitoring encompasses seasonal, environmental and population variation, and trends or responses by fish populations to such variation can be used to identify parameters that influence migration behaviour (Peterson et al., 2017). Formation of algae, and the consequent lowering/zeroing of visibility, is a relevant issue in many rivers for all the video monitoring systems, that may require adequate and intensive maintenance interventions.

Four established technologies for camera-based fish migration monitoring are described in further detail:

The automatic fish counter RIVERWATCHER, from the Icelandic manufacturer VAKI, is a passive, contactless (non-invasive) counting device, which enables fish to pass the counter without delay or being trapped. Migrating fish are guided through a passage chute where infrared scanners detect, measure, determine direction and record passing objects. The functionality of the RIVERWATCHER for long-term monitoring has been established in several central European rivers and the United States, including rivers with high species diversity (Schletterer et al., 2015; Haas et al., 2018). Costs for a scanner amount to 36,000 EUR, and to 57,000 EUR per installation for a combined system (scanner + camera); additionally site specific fykes (special nets to trap/guide fish) need to be constructed. In Europe, well documented installations are located at the Mosel River (Groß, 2014), the Lachsbach (Haas et al., 2018), as well as along the Inn River (Schletterer et al., 2015; Haas et al., 2018). Camera systems can be limited by turbidity (e.g. due to glacier melt in summer), thus the RIVERWATCHER System (combining infrared scanner + camera) is the most suitable in such systems. These systems are often used for "standard monitoring campaigns", e.g., in autumn or spring. In some cases (e.g. BfG + TIWAG[10]) the RIVERWATCHER systems are operated over a longer time period, which can be an important tool to analyse seasonal fish migration patterns, but also to evaluate potential relationships between abiotic factors and fish migration, as every passage record is associated with the direction, date, time and water temperature (Haas et al., 2018).

The FISHCAM hardware records automatically high-resolution video clips of migrating fish and drifts particles without hydraulic influence, without trapping, contact or stress for fish, in a detection tunnel, using a LAN camera (Mader et al., 2017a, 2017b). The robust image classification algorithm, used in the FishNet software, is able to detect and track moving objects from the recorded videos and separate Fish from NoFish moving objects using the Deep Convolutional Neural Networks technology with an accuracy rate of >97 % (Mader and Käfer, 2020). Costs for a FISHCAM amount to 25,000 EUR per installation. The applications along the Drava river are well documented (e.g. Mader et al., 2020; Brandl et al., 2022).

The HYDROCAM was specifically developed by Tallinn University of Technology for I AM HYDRO GmbH to monitor fish and is designed for continuous long-term or temporary use in water at depths up to 30 m (I AM HYDRO, 2022). The system includes a stereo infrared and RGB color camera system with a wiper as well as infrared, white and ultraviolet, lighting. It allows for cellular or satellite communications, and can be powered using a standard power plug, power over ethernet or solar battery for remote locations. The HYDROCAM uses Mobotix terrestrial surveillance cameras and offers the user a wide range of possibilities without having to resort to additional software. The systems are flexible and versatile due to their robustness and compact design.[11] Costs for a HYDROCAM amount to approx. 11,000 EUR per installation. Several applications were made so far, the application for migration analyses of brown trout in the Hasliaare river in Switzerland is well documented (see Reuther, 2022).

The Finnish based FISHHEART[12] has also developed a unique system to facilitate fish passage over large dams and this system also includes a monitoring unit. The modular system has a floating entrance which is a complex unit to attract, sort and transfer fish over dams at any given sites. The entrance unit is equipped with monitoring modules where fish are observed in a tube and their characteristics are registered. While being filmed, deep-learning techniques recognize the fish species in order to allow or halt their migration over the dam. Invasive species are detected and can be sorted out in given sites. The system is robust, but costly to run depending on site-specific characteristics. The company Fortum implemented a Fishheart fishway at Leppikoski hydropower plant in Paltamo in August 2021 and in the first year of operation >12,500 fish safely passed (Fortum, 2022).

2.4.5. Statistical models and telemetric biosensors

Environmental variables can be monitored to detect the general pattern of seasonal migration of fish species. When the real-time monitoring by camera is not possible, migratory models can be developed by simple regression between the timing and the monitored environmental variables. When such models are available, they can be used to predict the timing of migration near hydropower installations (Fjeldstad et al., 2012), by monitoring the indicative environmental variables (e.g. discharge, water temperature). Meanwhile, hydropower operators control their hydropower system in real-time by DICC in favour of migratory fish, e.g., diadromous fish (e.g. European Eel). Measures that can be combined are short-term reduction of hydropower production, increase diversion flows towards safe alternatives during downstream migration of fish, or to increase

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[10] These are 2 organisations using the Riverwatcher for long term monitoring: Bundesanstalt für Gewässerkunde, Germany + TIWAG -Tiroler Wasserkraft AG, Austria.

[11] https://iamhydro.com/en/equipment/hydrocam-system.php.

[12] https://fishheart.com/products#fish-passage-solution.

attraction flows towards fishways during upstream migration. In Fjeldstad et al. (2012) it was shown that the implemented measures contributed to increase the annual percentage of bypass migration from 11 % to 64 %.

The technique has been demonstrated for downstream migratory Atlantic salmon (*Salmo salar*) smolts in River Mandal in Southern Norway at the Laudal hydropower plant with the involvement of both researchers and the hydropower operators. They combined inexpensive telemetry technique (PIT) to monitor the route choice and timing of fish during migration season, and used existing loggers for monitoring the environment. With the acquired data, a simple regression model has been developed and used to predict smolt migration. A measure to prevent smolt migration into the intake was to increase flow through already existing bypass section, located next to the intake entrance. By using the model with DICC, flow diversion through the bypass section was adjusted dynamically during the migration season, which resulted in significant increase of successful smolt passages at the site. The concept proved its relevance and even presented a cost-effective alternative for downstream migration of fish where screening systems would introduce high loss of power production.

Stage of development is TRL 7. It requires less expensive data collection on fish for each site where it will be used, and it needs to be validated with follow up fish monitoring (e.g. by using RFId-tag monitoring techniques). On the other hand, it gives opportunity to improve environmental performance of hydropower plants without significant investment to retrofit existing structures.

Yang et al. (2021) developed a telemetric biosensor that could allow for wirelessly monitoring the physiology, behaviour, and ambient conditions of tagged fish in real-time as they travel through fishways. Yang et al. (2022b) demonstrated a real-time underwater autonomous acoustic telemetry system to efficiently monitor the behaviour of migratory fish and environmental parameters. The system utilized edge computing to filter and compress raw detection data by over 2000 times so that it could be transmitted acoustically to a shore-based system up to 3.5 km away, where it could be uploaded to a cloud and accessed in real-time with a web-based program.

3. Lithosphere

3.1. Sediment management

Sediment management is a key issue in river management and hydropower operation (Ausili et al., 2022). From the dam managers perspective, accumulation of sediments in the reservoir generates several adverse consequences, such as loss of storage capacity, dam vulnerability in case of earthquake hazard, bottom outlet obstruction, abrasion risk on intakes and hydraulic turbines. The interruption of the sediment flux continuity is highly relevant, with consequent alteration of the geomorphological features of the downstream river reach. River sediment accumulation poses a challenge towards increased flood risks (reduced channel discharge capacity), instream biological impacts (e.g. degradation of fish spawning areas/ rearing habitats and biodiversity) and robustness of various implemented river restoration means (e.g. spawning gravel, etc.). Furthermore, accumulation of sediments upstream of dams reduces downstream fertilization (e.g. aquatic organisms and irrigation) due to lack of sediments and nutrients, and poses a downstream pollution risk or even release of anoxic water (black water) if flushed (Hauer et al., 2018). Reservoir sedimentation can also affect the river ecosystem, e.g., extra flooding due to channel aggradation upstream of the reservoir, incision of river channels, reduction of nutrient supply and alteration of river morphology and bottom substrates downstream of the dam (Doretto et al., 2019). Sediment removal by mechanical dredging or controlled sediment flushing can be necessary for ensuring the technical functionality of the hydropower plant, but can have considerable and far-reaching ecological consequences if not adequately managed (e.g. Espa et al., 2016; Crosa et al., 2010). However, it is important to distinguish between reservoir flushing (high concentrations, short time period, e.g., during a flood event, with the aim to remove sediments from the reservoir) and a controlled drawdown (low concentrations, longer time period, with the aim to empty the reservoir) (Hauer et al., 2018). The high sediment load released downstream during these interventions can be extremely harmful for the aquatic ecosystems, e.g. leading to direct fish mortality and significant habitat alterations. Direct and acute hypoxia after a flushing would become a critical factor if the suspended sediments exceed $30\,\mathrm{g\,l^{-1}}$ leading to a DO of $<2\,\mathrm{mg\,l^{-1}}$ (Hauer et al., 2018).

Therefore, the importance of properly managing sediments has been now well recognized in the Water Framework Directive (WFD) (Ausili et al., 2022). The understanding of all the process, from continuous monitoring of suspended sediments (Hauer et al., 2018; Hauer et al., 2020) and bed-load transport with direct (basket sampler or bed-load trap) and indirect methods (geophone system) (e.g. Liedermann et al., 2019; Bock et al., 2019), is thus essential, and appropriate sediment management strategies (Palmieri et al., 2001) have to be implemented in order to minimize the adverse impacts. In the recent years, novel technologies are under development for real-time control (Felix et al., 2016; Bishwakarma and Støle, 2008; Peteuil et al., 2014; Hauer et al., 2018; Habersack et al., 2019), with several benefits, discussed in the paragraph below.

During controlled sediment flushing, sediment concentration measurements at subsequent river sections downstream the reservoir can be used to regulate in real-time the release of additional discharge from the dam, to dilute the sediment load below the threshold values deemed to be critical for the aquatic ecosystems. However, the definition of appropriate thresholds for sediment concentration (e.g. turbidity, suspended solids, dissolved oxygen, etc.) and operational difficulties in controlling them during the flushing activities constitute a critical issue for an efficient implementation of this approach (Crosa et al., 2010). Sediment monitoring allows to verify that the magnitude of the effective impact is conformed to expectations, to identify and understand as soon as possible non-expected evolutions, and to define mitigation measures to improve environmental sustainability and reduce impacts. One short-term strategy is the temporary shutdown of turbines and gates maneuvers (Peteuil et al., 2014), that can help in reducing turbine erosion.

Current sensors are able to measure at high frequencies, and, therefore, detect the temporal variability of sediment properties. However, the major limitation of sensors is their need for calibration, which is mostly site-specific and complicated by the control of sediment parameters. For instance, turbidity does not only depend on the suspended sediment concentration, but is modified by grain size and color, introducing a variable amount of uncertainty to the calibration of the sensor data (Hoffmann et al., 2017). Existing sediment concentration instruments, like acoustic backscattering and optical turbidity probes, require regular calibration by taking water samples, limiting the real-time capability. One novel technology to overcome these challenges is SediScat, a multi-frequency acoustic instrument tested successfully in the laboratory, to measure sediment concentration and the mean grain size continuously at a hydropower plant (Rai et al., 2016).

The HYPOS project,[13] supported by the European Commission, focuses on highly spatial-temporal resolved data through multi-satellite sensor services, focusing on turbidity and suspended sediment loads. The project aims to provide an easy access to satellite-based measurements for hydropower application. Monitoring systems are under implementation in 4 pilot cases: Enguri and Vardnili hydropower plants (Georgia), Gebidem hydropower plant (Switzerland), Verbois and Chancy Pougny hydropower plant (France&Switzerland) and Banja hydropower plant (Albania).

3.2. Seepages and leakages

Hydropower plants, especially the larger ones, use civil and conveyance structures to store and transport water (reservoirs, tunnels, canals, penstocks, pressure shafts). One of the problems that may arise in these structures are leakages and seepages, where the former term generally

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[13] https://hypos-project.eu/use-cases/.

indicates the escape of water through fittings, creeping joints or small cracks, while the latter the slow escape of a liquid or gas through porous material. Such water losses, which are not generally associated to polluted water, undermine hydropower production, as well as may generate stability problems of slopes and accelerate dam deterioration (Basnet and Panthi, 2018; Zhang et al., 2021; Huang and Chen, 2012).

Real-time inspection, monitoring and modelling can be implemented to detect water losses. Sensors can be used especially for penstocks (Walsh and Prien, 1995), while Remote Controlled Vehicles and underwater drones have been introduced for monitoring if there have been a slide or severe rock fall in headrace tunnels, and can also be used to monitor the status of pipes and tunnels (e.g., https://www.ntias.no/, http://oehagen.no). As of today, there are many limitations in the use of such equipment. Cable connection to the equipment while performing such "remote inspections" of water filled tunnels is one big challenge as of today and set clear limitations. Assigning geographical positions to the collected data is challenging, since GPS-system does not work in tunnels.

4. Atmosphere

4.1. Methane and carbon emissions from reservoirs

Methane (CH4) and carbon dioxide (CO2) are mainly generated as a consequence of the decomposition of organic matter in a hydropower reservoir, depending on the geographic context, climate and reservoir type. From Alpine hydropower reservoirs, only minor methane emissions are known (Sollberger et al., 2017; Pighini et al., 2018), while the situation may be relevant in the lowlands (Kemenes et al., 2007) and in tropical reservoirs. Methane can be transferred from a reservoir to the environment through different processes: (1) direct flux across the air-water interface at the surface of the reservoir, (2) turbulent exchange with the atmosphere immediately downstream of the hydroelectric turbines (degassing), and (3) flux across the air-water interface in the river downstream. Furthermore, methane can be transported by either diffusion or ebullition to the atmosphere; methane can also be oxidized in the water column and be emitted as CO2 (Barros et al., 2011).

Real-time monitoring of CH4 emission (e.g., Xiao et al., 2015) could help in understanding the amount of organic sediments trapped in a reservoir under decomposition. Estimates of reservoir CH4 emissions could also be improved through remote sensing data from satellites (Delwiche et al., 2022), or be estimated by the G-RES tool (Prairie et al., 2021). The real-time monitoring could be used to activate mitigation measures, e.g., methane capture systems (Kikuchi and do Amaral, 2008) or the selection of the optimal inflow gate (in case of multiple inflow gates) to the turbine, in order to control (in real-time) methane and carbon released downstream. Novel technologies are under study to capture the degassing methane, for example the system described in Kikuchi and do Amaral (2008), or the technology under investigation by the company Bluemethane. The amount of degassing methane that could be captured was quantified in 5950 t/year in Europe (Quaranta and Muntean, 2023). However, the TRL is still low, and these technologies are mostly at the lab testing phase.

4.2. Evaporation from reservoirs

The change in land surface and alteration of water cycle caused by reservoirs can lead to change in radiation and storage of various greenhouse gases, and eventually disturb the interaction between water and atmosphere, along with local climate behaviors (Zhao et al., 2021). Evaporation reduces water availability and, therefore, hydropower generation, while increasing humidity of the surrounding environment. The aggregated blue water footprint (i.e., evaporation) of the hydropower plants analyzed by Mekonnen and Hoekstra (2012), representing 8 % of the global installed hydroelectric capacity, was 90 $Gm^3\ yr^{-1}$, which is equivalent to 10 % of the blue water footprint of global crop production in the year 2000. Vanham et al. (2019) calculated that evaporation from hydropower reservoirs is 9114 $m^3\ TJ^{-1}$ in the European Union. Therefore, evaporation estimation, especially in large reservoirs, is important for an accurate prediction of water availability within the reservoir. As the interest on floating photovoltaic technology is growing (Cazzaniga and Rosa-Clot, 2021), the real-time monitoring of photovoltaic (PV) energy output could be used to estimate the solar radiation and, as a consequence, the evaporation from the reservoir. Although no measure, operated in real-time, exists to reduce evaporation, it is estimated that by covering 10 % of the hydropower reservoirs surface in the EU with floating PV, 0.05 % of water flow could be saved from evaporation (Quaranta et al., 2021).

5. Discussion

The achievement of a trade-off between the need for renewable energy and hydropower and the conservation of ecosystems poses a challenge for resource managers and policy makers (Carolli et al., 2023). This of high relevance especially in the European Union, where issues surrounding dams are at the heart of the green energy transition, the new biodiversity strategy and the Water Framework Directive (Appendix 6). In Europe, the WFD defined targets for EFlows and the approaches were recently summarized in CIS guidance document n°31. In this context, DICC is an effective strategy to support the integration of hydropower into the Earth spheres, based on reliable information. DICC entails improvements in the environmental status of ecosystems and positive imprints on hydropower operation, maintenance and energy generation.

In the next sections, results are discussed focusing on the transversal benefits of DICC and the several interconnections among the Earth spheres (Fig. 3), with special emphasis on the European context.

5.1. Water quality

The water quality indicators that are discussed in this study are oxygen concentration, pollutants, water temperature and oil spills.

Low oxygen concentrations, but also supersaturation, can impose problems on biota, and may be a meaningful indicator to reveal anomalous behaviour in the aeration systems (e.g., the casing of Pelton turbines (Quaranta and Trivedi, 2021)). Aerated draft tubes can help mitigating oxygen anomalies, and can also improve the operation of Francis turbines at part load (Kougias et al., 2019). However, there is much room for technical enhancements through changes in the design or the logic of the real-time control system. Self-aerated draft tubes needs to be tested on turbines of larger sizes (in the range of those installed in deep hydropower reservoirs).

Recent studies have shown that rising air temperatures and extreme heatwaves have generated a significant increase of river water temperature. The temperature raise entails several impacts, such as accelerated biochemical metabolism, inability to reproduce successfully and mortality for some aquatic species (Feng et al., 2018; Bui et al., 2018). This is important in the European context, especially in the light of climate changes and heat waves in summer. Empirical studies on mitigation measures of water temperature fluctuation are a few, and the effects of good practice of environmental design and targeted mitigation measures are, unfortunately, not well documented. Thermopeaking alterations in downstream river sections may paradoxically be a potential mitigation strategy in certain cases, as it reduces water temperature oscillations. Saadatpour et al. (2021) suggested that future studies should examine techniques which are capable of finding multiple efficient infilling points (through which water is withdrawn from the reservoir and discharged) with less computational efforts. Also ice formation may pose special problems for hydropower systems (head losses, incomplete turbine shutdown, flooding, gate blockage, flow reduction) (Gebre et al., 2014). Web cameras can be used to monitor real-time ice conditions at hydropower plants (Vuyovich et al., 2009). However, as experienced at many sites in Norway, the available data on ice are sparse, which makes analysis and operational strategies difficult (Gebre et al., 2013). Thus, there is a crucial need for more empirical data, especially from long-term studies.

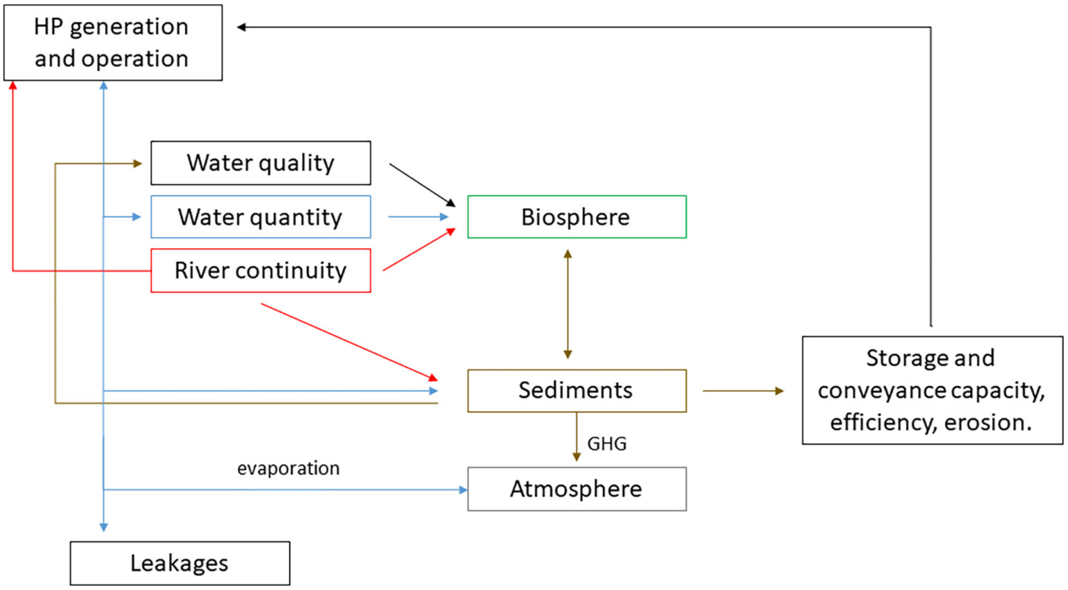

Fig. 3. Interconnections between the Earth spheres.

Nitrogen and Phosphorous can be retained in reservoirs, thus an optimal control of reservoirs could help in minimizing downstream pollution during extreme polluting events. It is estimated that 17 % of global river phosphorous load will be retained in reservoirs by 2030 (Maavara et al., 2015). Reduction of Nitrogen and Phosphorous in EU rivers is an important issue to be considered. In an analogous way, combined sewer overflows can be mitigated by a proper reservoir management and adequate releases operated in real-time. However, since they are chronic problems not associated to hydropower operation, they should be addressed at the source (i.e. intensive agricultural activities, inefficient wastewater treatment) (Blaas and Kroeze, 2016; Grizzetti et al., 2012) and not by hydropower and reservoir operators.

Detection of anomalous oil concentrations close to HPPs may reveal damages of the lubricating system of the turbines. To date, several Kaplan-Bulb and Francis turbines have been upgraded so as to make them work free from oil (Värlind, 2002; Falkenhem et al., 2011; Auger and Ren, 2017), and new materials and lubricants are being developed (Quaranta and Davies, 2021). Oil-free hubs are already present in Europe, particularly in the Scandinavian countries, and oil spills do not seem a chronic problem in Europe.

Hence reservoir operation may be a key action for improving sustainability and environmental quality, especially the multi-purpose reservoirs. The multi-objective demands, along with limited water resources, have brought water quality aspects to forefront in reservoir management problems. While the techniques to improve water quality in water resources systems are often very expensive, artificial intelligence and stochastic techniques are emerging as suitable tools to optimize multi-purpose reservoirs and different objectives, including the chemical quality and reservoir storage (Sorkhabi et al., 2022). Optimization methods can be applied to determine long-range operational policies (weekly, monthly, and seasonal), and real-time optimization can be utilized to evaluate and update such long-term guidelines over shorter time horizons (hourly or daily time increments), in conjunction with real-time forecasting of inflows and monitoring of the actual conditions (Teegavarapu et al., 2013; Hülsmann et al., 2021).

5.2. Water quantity

A better modulation of the Eflow, based on DICC, may allow to reduce its release in certain cases, and hence to increase hydropower generation. Appropriate manoeuver systems of intake gates should be developed in order to release the correct amount of water to secure satisfactory living conditions for fish throughout a year. Most of the intake gates installed in the hydropower industry are neither designed to release a small amount of water nor being operative for frequent regulating a flow as needed. Implementing real-time monitoring systems of incoming and released discharges at dams and weirs can even constitute an additional node of the institutional hydrological monitoring networks. Real-time flow monitoring devices are already available on the market and can be linked to automatic devices that operate gates or turbines to regulate the flow released downstream of the dam. Real-time control can help to better schedule the power plant operation and turbine shutdown. Periods of turbine shutdown could be exploited to perform maintenance works, while improving fish passage.

5.3. Hydropeaking

Hydropeaking is highly multidisciplinary and requires a proper understanding of the riverine biota, the geomorphological dynamics of the river, as well as sound knowledge of civil, hydraulic, electrical and control engineering (Batalla et al., 2021). A European survey asked 30 European countries if mitigation of rapidly changing flows (incl. effects of hydropeaking) was included in the national list of mitigation measures. Twelve countries answered “yes”, nine of them said the topic is not relevant, seven did not give a statement and two identified the impact, but did not present any measure (Moreira et al., 2019).

Compensation basins are an important strategy for hydropower operators for hydropeaking mitigation, but there is limited experience on its real-time control. Due to its apparently strong case-dependency, future projects will have to face several different technical challenges. The logic of the real-time control system aimed to control the water output from (and, in some cases, input to) the compensation basin depends on each project configuration and features, such as the dynamics of the waterways conveying the water to the compensation basin, the installed water regulation devices (valves, gates, etc.) and the installation of additional turbine (and in some cases pump) units. Having in mind the more and more demanding energy regulation need, it is reasonable to assume that further compensation basins for hydropeaking mitigation will be commissioned in the next future. Also hydropeaking diversion HPPs comprise a promising solution, depending on site specific criteria. In Norway a couple of HPPs discharge peak flows directly to the sea. The most important challenge of bio-hydrological and etho-hydraulic modelling is that models have to be previously developed under controlled conditions, and have to focus on different components on the river ecosystems and on different species or functional groups to be widely applied. Once developed, models are reliable and could underlie any management decision in a power plant, as they provide objective and quantitative information about environmental scenarios related to hydropower operation.

5.4. River continuity: upstream and downstream fish passage facilities

At least 1.2 million instream barriers (of any type) in 36 European countries (with a mean density of 0.74 barriers per kilometre) exist (Belletti et al., 2020), which poses the light on the high importance of river connectivity restoration measures. Hydropower barriers represent a percentage of this, below 10 %.

Relating fish movement and behaviour to environmental variables during their migration can increase notably the number of fish that move through fishways by managing/controlling hydraulic conditions inside and around the devices (Fuentes-Pérez et al., 2021). Moreover, detecting the hours/time of the day and season when fish are migrating can optimize the fishway operation, even limiting losses in hydropower energy production. Passage over dams can be improved by using DICC techniques for fish species which migrate in correlation of known environmental conditions. Even though such indicative conditions have only been studied to a few species, the presented concept of combining statistical models with conveyance measures is a potential tool to improve safe passage for fish over hydropower installations. Moreover, data collection for every field application contributes to the general knowledge of fish species and their migration patterns in different systems.

5.5. Sediment management

A proper sediment management in real time can generate multiple benefits for hydropower operation and on the environment. By a proper sediment management it is possible to reduce turbine erosion (and increase efficiency, e.g., up to 8 % in Felix et al., 2016a) and the wear of the electro-mechanical equipment (e.g., up to 10.50 μm/month in (Guangjie et al., 2013)), and to facilitate intervention. In Europe, 0.73 % of reservoir volume is annually lost due to sedimentation, while it is 0.22 % in US, 1.2 % in Turkey, 2.3 % in China (Schleiss et al., 2016). Trash racks can trap wastes that reach the water bodies, especially after intense storm events, helping in removing wastes in freshwater.

The use of real-time modelling, supported by real-time data combined with machine-learning models (Schleiss et al., 2016), can also eliminate the need to spend several million EURO in dredging to guarantee the navigation depths desired on rivers which combine hydropower and navigation (Ackermann et al., 2000).

5.6. Final remarks and implications for the EU

Table 1 summarizes the main findings of this review and highlights the advancement status of the analyzed technologies, with their limitations, relevance and challenges, with focus on the EU context. In the EU, the three most relevant and urgent topics seem to be Eflow modulation and hydropeaking mitigation to avoid deterioration of downstream ecosystems, and the improvement of fish passage efficiency. It must be noted, in the EU, less than 10% of barriers are for hydropower purposes. In other countries, priorities may be different, whereas in some emerging countries the main current priority is to increase renewable energy generation rather than to mitigate the impacts on the environment. For example, in tropical reservoirs (e.g., in Brazil) carbon and methane emissions, and evaporation, are relevant and strategies to mitigate them are evenly relevant. If methane emissions from the 187 world largest reservoirs would be captured with the assumed efficiency of 60 %, 19 % of total methane emissions could be saved, which would reduce the overall carbon footprint of global hydropower by 8 % (Scherer and Pfister, 2016). The identified strategies, summarized in Table 1, can be used by scientists and policymakers all over the world to assign the right priorities to strategies and research programs, depending on the urgency and relevance of the identified problems.

DICC is an emerging strategy not only in the hydropower sector, but in any water-energy related sector (Garrido-Baserba et al., 2020; Negm et al., 2023; Voutchkov, 2019; Wang et al., 2022). In water distribution networks DICC allows to reduce leakages and to control the pressure at the hydraulic nodes (Creaco et al., 2019; Fontana et al., 2019), and in combined sewer networks DICC allows to reduce combined sewer overflows (Quaranta et al., 2022a). In agriculture, DICC improves the irrigation schedule (Beeri and Peled, 2009; Kitchen, 2008).

DICC can also be used to monitor, in general, water quality and quantity, and to prevent, or mitigate, impacts on/from the Earth spheres, which are not necessarily caused by barriers and reservoirs. For example, an EU report published mid-February 2023 (Free et al., 2023) analyses the massive fish kill (360 tonnes) in the Oder River in July and August 2022, one of the largest ecological disasters in Europe in recent memory. A key factor enabling the proliferation of this species was the high salinity of the river during this time, probably in part resulting from discharges of saline industrial wastewater, e.g., from mining. Other contributing factors were the drought, low water levels (reducing dilution and flow) and hydromorphological modifications to the river. High nutrient concentrations, especially phosphorus and nitrogen, are also key in promoting such blooms. To prevent such events occurring in future, the report recommends to improve online monitoring and the mandatory communication of pollution events across international river basin districts, review and implement dynamic control of licenced discharges and review the role of hydromorphological modifications in slowing the flow (which, in turn, allows time for blooms to develop).

6. Conclusions

Digitalization, information, communication and real-time control (DICC) in the hydropower sector is an emerging strategy, that until now has been mainly implemented and researched with regards to the improvement of the efficiency and for the evident benefits in the Operation and Maintenance sector. In this contribution, we presented innovative approaches and discussed the benefits of DICC on the environmental performance of hydropower plants and barriers, with case studies, opportunities and challenges. Data can be utilized by researchers, regulatory and industrial communities to determine the technological priorities and relevance in their geographic contexts. Although frequently considered as conflicting, we provide new opportunities to link environmental and energy goals together, primarily through the coordination and large-scale implementation of digital monitoring technologies. Multiple benefits include increased generation, improved environmental sustainability, increased operational reliability and reduced maintenance expenditure, and a more comprehensive knowledge base for complex management decisions and strategic planning. Although the focus was the hydropower sector, the discussed strategies are of relevance and applicability in any artificial barrier and water reservoir that interferes with the hydrosphere.

The main discussed topics were water quality (oxygen concentration, oil spillages, temperature, ice), hydropeaking, fish passage facilities and bypasses, control of the environmental flow (Eflow), withdrawals and releases, sediment management, leakages and methane and carbon emissions from reservoirs.

DICC is of high relevance worldwide, and should be considered both in greenfield projects and in modernization (e.g., refurbishment, retrofitting) projects. In the EU, DICC can contribute to reaching WFD objectives, in line with the renewable energy targets set by the European Commission (e.g., REPowerEU). DICC fosters the EU digital transition, along-side with the green and renewable energy transition promoted in the Green Deal. The three most relevant topics for the EU are Eflow modulation, hydropeaking mitigation and the improvement of fish passage efficiency, where the implementation of DICC could give a significant contribution.

Digital technologies have the advantage that are less invasive and in most cases can be quickly implemented and updated. However, digital technologies are subject to security attacks (physical attacks on sensors, cloning, data theft, high dependence to centralized servers) and cyber

Table 1

List of the discussed topics. The adjusting technique is any process supported by DICC to improve the environmental parameter listed in the column “Monitored parameter”, when low quality values are detected by the DICC.

Monitored parameter by DICC	Adjusting technique supported by DICC	TRL	Implementation difficulties	Future challenges	Comment and relevance in the European Union
Water level	Gate opening, discharged flow.	9	Control of more output simultaneously.		This technology is already implemented and affirmed globally.
Water quality: dissolved oxygen and TDG	Flow and water release modulation and regulation, water mixing in the reservoir, self-aerated draft tubes controlled in real-time.	8	Additional engineering works.	Need to test more full scale self-aerated draft tubes.	In European rivers, oxygen consuming substances (BOD) decreased over the period 1992 to 2019, largely thanks to the introduction of the Urban Waste Water Treatment Directive (Vigiak et al., 2019).
Water quality: temperature	Water mixing, forced circulation, submerged curtains, flow regulation.	8	Optimization of selective withdrawal systems.	Need for more empirical data.	Forecasts predict more frequent and extreme heatwave events in Europe. In the Alps, hydropower flow and water temperature are modified through the intermittent release of flow that takes place mostly at daily and sub-daily frequencies (Feng et al., 2018).
Water quality: biological and chemical pollutants	Multi-objective optimization of reservoirs and turbine inflow regulation.	8	The water quality model needs to be calibrated for any process-specific parameters using available observed data.	Chronic problem, should be managed at the source point and not by operators. For example, 1656–4997 t/year of macroplastic are estimated reaching the ocean in Europe (González-Fernández et al., 2021).	
Water quality: oil spills	Emergency maintenance.	9	Oil is delicate to handle.	Implement a DICC system rather than occasional inspection.	The European use of lubricant oil for hydropower is 0.0022 % of the consumed oil as primary energy (Quaranta, 2023). Not very relevant. Several HPPs in Northern Europe use oil-free turbines.
Hydropeaking	Compensation basins operated in real-time.	9	Site specific, complex logics and models (bio-hydrological models, etho-hydraulic models, with TRL = 4).	Previous development of generalizable models under controlled conditions.	Depending on local conditions and country conditions (Moreira et al., 2019). Only few European countries (Switzerland and Austria) have legal regulations regarding hydropeaking flow thresholds. However, the WFD does not specify methods, targets or thresholds for hydropeaking mitigation, but only refers to the achievement of the good ecological status or good ecological potential in all water bodies by 2027.
	Hydropeaking diversion power plants.	9	Models have to be previously developed under controlled conditions.		
	Operative measures (ramping rate thresholds)	9			
River continuity: upstream and downstream fish passage facilities	Smart Fishways.	7	Determining the minimum number of sensors, developing a methodological framework adaptable to all possible study cases with few tuning parameters, detecting best fishway configurations for fish, leaving aside other environmental cofactors.	Lack of EU standards addressing the data collected.	High relevant problem in Europe due to the very high river fragmentation. At least 1.2 million instream barriers in 36 European countries (with a mean density of 0.74 barriers per kilometre), 68 % of which are structures <2 m in height that are often overlooked (Belletti et al., 2020). 630,000 barriers counted in the AMBER EU Atlas, and hydropower barriers are below 10 %. Strategies can be supported by statistical models (TRL = 7) and video monitoring (TRL = 9). However, the former are limited to fish species which migrate seasonally, are site-specific, need of validation in each site, and several years of data are required. Video monitoring is a strategy that can support all the techniques, but it is expensive, and turbidity influences the operation.
	Bypasses with variable flowrates.	8	Additional electromechanical equipment, engineering and design efforts.	Commercialization, site-specific applications.	
	Turbine shutdown.	9	Energy generation reduction. Difficult to predict: video monitoring and statistical models can help to better implement turbine shutdown in real-time and with a better schedule, respectively.	Site-specific, need of a more flexible approach.	
Eflow, withdrawals and releases	Modelling	5–6	Need of long term hydrological models or 20 years of flow time series.	Short-term models can be produced with machine learning, but they have lower generalizability and may be difficult to use at different sites.	Very relevant as the main target of the Water Framework Directive. The proportion of the EU surface where rivers meet the water policy target, with a probability of at least 70 %, is 32 % (Grizzetti et al., 2017). There is sometimes poor transparency of the turbine regime of hydropower companies. The competition of water uses is also an issue in multiple use reservoirs. National regulations of water management are generally different, and therefore affect each country individually. The relationship with energy policies in the area is also a relevant issue. It is estimated that 90 % of the small HPP in the EU cannot be passed in upstream direction, and that for most of the plants no regulation exists concerning minimum flow. Taking into account minimum flow of Q95, this would lead to a reduction in HP electricity generation of 10 to 32 %. For large hydropower, a reduction of 5 to 20 % in generation was calculated for run river stations and 3 to 10 % for storage plants while a variation of 0.3 to 45 % for individual facilities was found (Arcadis, 2010).
	Habitat modelling (e.g. MesoHABSIM, CASiMiR)	8	Site-specific.	Lack of background data for many fish species, intensive field work needed for validation.	
	Monitoring	9	Discharge/water level measurement devices are to be selected site-specific.		
Sediment management	Gate maneuvers and opening, turbine shutdown, sediment management techniques (Hauer et al., 2018).	8	Continuous high costs for sediment dredging, treatment and deposition of the (fine) material out of the reservoirs.	Lack of process understanding, lack of knowledge about the quantitative consequences of sediment deficits.	In Europe, 0.73 % of the HPP reservoir volume is annually lost due to sedimentation.
CH4 and CO2 emissions from reservoirs	Carbon/methane capture processes.	4	Complex technological implementation of the capture technology.	Low TRL, need of big structures and power input, currently expensive.	Not as relevant in European reservoirs as in tropical reservoirs

security must not be overlooked. In some cases their programming and calibration may require years of data collection and evaluation.

Systematic quantitative data on the benefits of DICC on the environment are still missing. More case studies and quantitative data should be published to exemplify the benefits of DICC on the environment to better support its implementation. The risks and the challenges brought by DICC should represent an additional motivation for further research. DICC should be implemented in conjunction with adaptive management strategies, aiming to reduce uncertainty by increasing knowledge and understanding, thus enabling improved management decisions over time and mitigating impacts on/from all the Earth spheres.

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CRediT authorship contribution statement

All the authors conducted a literature review based on their knowledge. E.Q. coordinated the consultation and wrote the first draft of the paper. The authors are listed in alphabetic order after the first author.

Data availability

All the used data and information is included in the manuscript.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix 1

Table A1 lists the benefits achieved in the energy sector by the digitalization, which typically correspond to an increased efficiency (e.g., due to a better load distribution among different turbine units), less shutdown periods and less water spills thanks to a better inflow forecast. For more details see Quaranta and Hunt (2022). A state of the art SCADA (Supervisory Control and Data Acquisition) system for hydropower is 250 SCALA,[14] which facilitates real-time control of turbine governing, control of auxiliary functions, start/stop sequences, monitoring and control of external services (including environmental parameters) as well as communication to remote stations and control centers (e.g., that developed by Andritz Hydro).

Table A1

Benefits of digitalization in the energy context. From Quaranta and Hunt (2022).

Benefit type	Benefit value
Efficiency	+0.5 % +0.8 % (better loading of turbine units)
Efficiency, water availability	+ 1 % of efficiency and − 11 % spill reduction
Efficiency	+2 %, Kaplan-Bulb, by machine learning
Cost reduction	cost savings over 8 months due to the prevention of unplanned shutdowns were estimated in the range of 25 k€ to 100 k€ for a 1000 MW plant (Francis turbine)
Energy, cost saving	Globally, +42 TWh (+1 %) + annual operational savings of 5 $ billion
Efficiency, water availability, revenue	+1 % efficiency, −11 % spills, +10 % revenue

Appendix 2

DICC for water level control is the most implemented digital strategy. Water level sensors can be used to verify that the expected hydrodynamic conditions are present, or otherwise to activate gates and other hydraulic structures. The water level control can be implemented to guarantee the release of the environmental flow. DICC associated to water levels has been studied from a theoretical perspective for stability purposes of control systems in a wide number of case studies, such as those reported in Jiménez and Chaudhry (1992), Sarasúa et al. (2007) and Sarasúa et al. (2014). The control system uses the water level as an input variable and acts on the opening of the wicket gates or nozzles of the turbine, and in some cases on the opening of the intake gates. The current Technology Readiness Level (TRL) of this technology is the maximum (TRL = 9), meaning it is proven in operational environment. At present, the intensity of research on this control system is low, and is mostly focused on its adaptation to variable-speed hydro units. As a matter of fact, commercial turbine governors already incorporate the water level control function, and the logic of the control system are summarized in the international standard IEC 61362:2012.

Appendix 3

TRL 1 – basic principles observed.
TRL 2 – technology concept formulated.
TRL 3 – experimental proof of concept.
TRL 4 – technology validated in lab.
TRL 5 – technology validated in relevant environment (industrially relevant environment in the case of key enabling technologies).

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[14] https://de.scribd.com/document/390646988/SCALA-250-System-Description#.

TRL 6 – technology demonstrated in relevant environment (industrially relevant environment in the case of key enabling technologies).
TRL 7 – system prototype demonstration in operational environment.
TRL 8 – system complete and qualified.
TRL 9 – actual system proven in operational environment (competitive manufacturing in the case of key enabling technologies).

Appendix 4

Habitat modelling allows to compare different flow scenarios and their ecological effect (habitat suitability and availability) (Hubmann and Schletterer, 2016), which has become an important tool to develop an EFlow for a specific site. Here we describe two commonly applied models, i.e. MesoHabsim and CASiMiR.

MesoHabsim is a hydraulic-habitat model for estimating the Eflow. By applying this approach in a representative river reach downstream of the dam (habitat mapping at different river discharges, coupled with local fish fauna habitat suitability models), the flow released downstream the dam-weir measured in real-time can be directly assessed against the flow reference conditions. This allows to outline the changes in physical habitat conditions in the downstream reach and to identify possible stress conditions created by persistent limitations in habitat availability. In particular, the number of consecutive days that a habitat condition is allowed to continue under a specified threshold, before becoming catastrophic for the aquatic species, can be initially defined through the analysis of reference habitat time series and the UCUT (uniform continuous under-threshold) curve (Vezza et al., 2015). Therefore, the real-time monitoring of the released discharges can avoid exceeding that limit of consecutive days, implementing (even automatically) habitat augmentation strategies through short-term flow increases, aimed at interrupting the continuous duration of habitat under threshold.

CASiMiR-Fish is a habitat suitability model that imports results of 2D hydrodynamic modelling and relates them to the requirements of aquatic species, such as different life stages of fish species, macroinvertebrates or macrophytes. The model estimates quantitative information on the quality and availability of hydro-morphological habitats and their changes, caused by changes in hydrology (water depth), hydraulics (flow velocity) and morphology (substrate). In contrast to other habitat suitability models, it is based on a multivariate approach that is able to integrate rules for the description of habitat requirements. These rules are generated based on data evaluation and/or ecological expertise (e.g. Hubmann and Schletterer, 2016). CASiMiR-Migration is an agent-based model, which enables to analyse the effectiveness of the attraction flow downstream of fish passes (Kopecki et al., 2016). It is based on the evaluation of hydraulic features, such as flow velocity (magnitude, direction and gradient), as well as morphological features such as river bottom gradients, vicinity of flow obstacles to predict favourable and unfavourable swimming paths for migratory fish. This tool allows to couple the ecological condition of an aquatic ecosystem is directly coupled with the living conditions of the typical resident species.

Appendix 5

First Study Case: submerged notch and orifice fishway in Guma, Duero River.

It is a fishway located in the Duero River, near Guma village in the northwest part of Spain (41°38′13.9″N, 3°32′36.9″W) (Fig. A1). The fishway is composed by 36 cross-walls with submerged notches and bottom orifices (notch width (b_n) = 0.3 m; sill height (p) = 0.8 m; orifice size = 0.175 m (width-b_o) x 0.175 m (height-a_o) and 35 pools (length = 2.6 m; width = 1.6 m; slope = 8.6 %), with mean water drops (ΔH) of 0.25 m, mean water depth in the pools (h_O) of 1.2 m and volumetric power dissipation of 121 ± 10 W/m^3.

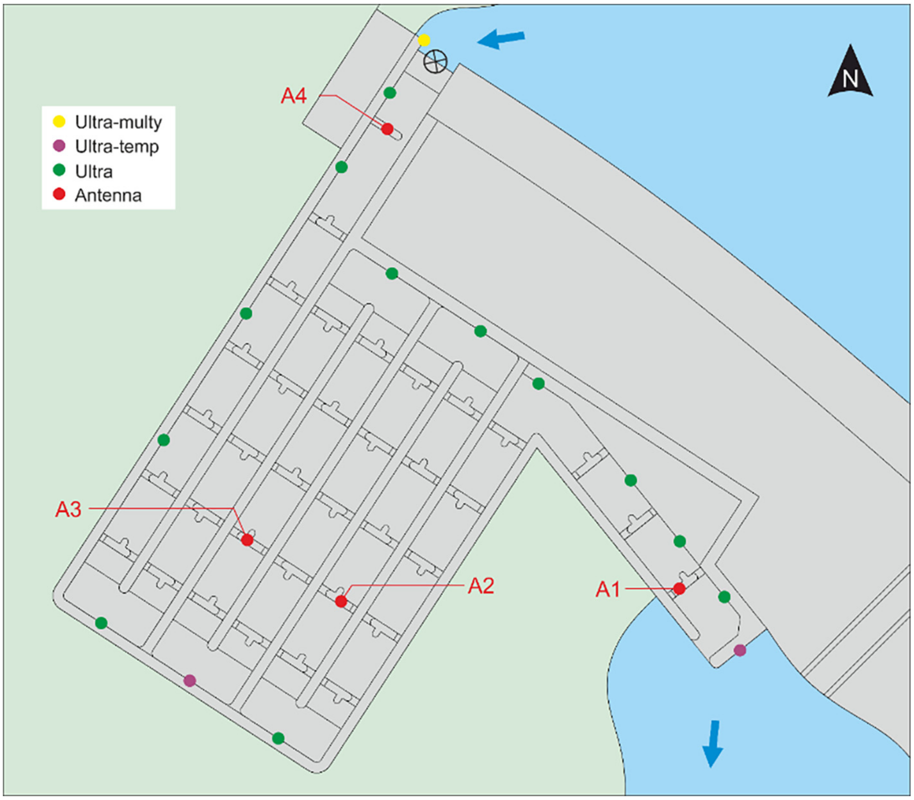


Fig. A1. Installation of the sensor network at Guma.

Total cost estimated for *Smart Fishways* implementation: 12,500 EUR (the cost include the PIT-tag - Passive Integrated Transponders- system, but excludes the fish counter).

The sensor network consists of 15 sensors (Fig. A1):

- 12 nodes with ultrasound water level sensors.
- 1 node with ultrasound water level sensors, water temperature, barometric pressure, air temperature, humidity, and luminosity sensors.
- 2 nodes with ultrasound water level sensors and water temperature sensor.

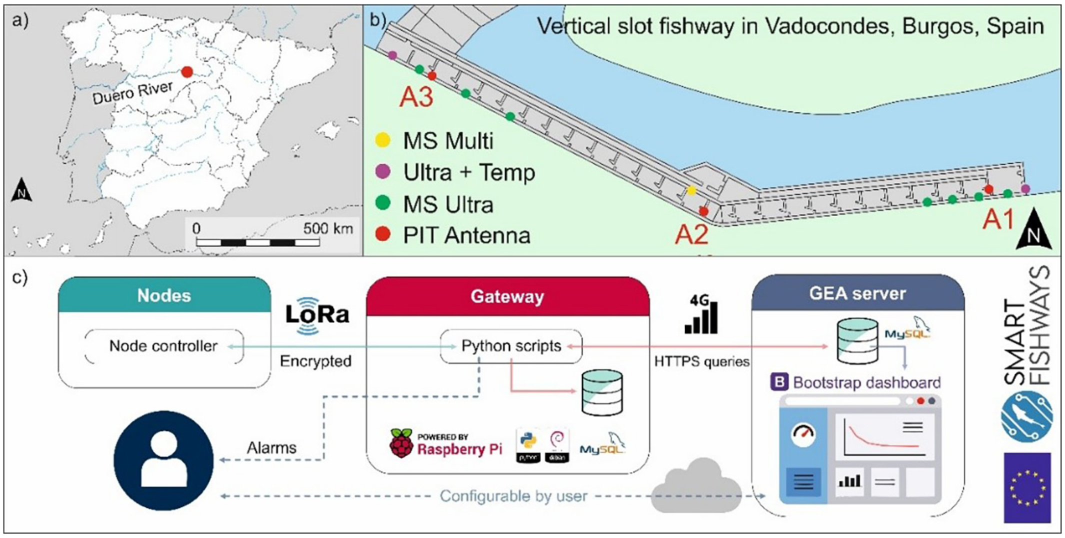
In addition, together with the sensors to collect biological information a PIT-Tag system with 4 antennas has been installed, which would be substituted by a custom-developed fish counter in the next monitoring campaign (2023).

All the data is collected, processed, and transmitted (Lora radio + mobile connectivity) by a single Gateway that consists of a Raspberry Pi computer.

Second Study Case: vertical Slot fishway in Vadocondes, Duero River.

It is a fishway located in the mainstem of the Duero River, in Vadocondes village (Burgos) in the northwest part of Spain (41°38′16 ″ N, 3°34′17″ W) (Fig. A2a and b). It is a vertical slot fishway composed of 26 cross-walls (slot width (b_s) = 0.2 m) and 25 pools (length = 2.1 m; width = 1.6 m; slope = 6.5 %) with mean water drops (ΔH) of 0.15 m, mean water depth in the pools (h_0) of 0.92 m, and mean volumetric power dissipation of 122 ± 7 W/m^3.

Total cost estimated: 11,500 EUR (the cost include the PIT-tag system but excludes the fish counter).Fig. A2Installation of the sensor network at Vadocondes.



The sensor network consists of 10 sensors (Fig. A2c):

- 12 nodes with ultrasound water level sensors.
- 1 node with ultrasound water level sensor, water temperature, barometric pressure, air temperature, humidity, and luminosity sensors.
- 2 nodes with ultrasound water level sensor and water temperature sensor.

In addition, together with the sensors to collect biological information a PIT-Tag system with 2 antennas has been installed, which would be substituted by a custom-developed fish counter in the next monitoring campaign (2023).

All the data is collected, processed, and transmitted (Lora radio + mobile connectivity) by a single Gateway that consists of a Raspberry Pi computer.

Data management and operational decisions in Smart Fishways

Concerning operational decisions in the hydropower facility, the processing of the data includes an autonomous algorithm to detect hydraulic anomalies on the fishways. This algorithm consists of a pre-trained classification neural network that compares the current performance of the fishway with the expected performance, detecting obstructions or other possible alterations (e.g. clogging of the fishway) (Fuentes-Pérez et al., 2021). Once an anomaly regarding water levels, in comparison with expected hydraulic performance, is detected, this triggers an alarm for inspection to operators.

Additionally, fish passage data from PIT-Tag system[15] is automatically processed and filtered through a custom logical algorithm, which allows the real-time counting of downstream/upstream passages, as well as counting the number of tagged fish inside the fishway. This information is available for the operators or researchers to plan any possible operation/action in the fishway or hydropower strategy (e.g. increase attraction discharge).

The next and last step consists of training a Random Forest model considering past passage events and all environmental variables collected to identify those situations that trigger the maximum number of fish movements (see García-Vega et al. 2018 and 2022) (Fig. A3). After, considering factors that can be altered (such as boundary conditions in the rivers by operating the power plant or optimizing discharge and water drops inside the fishway by upstream and downstream control gates), together with the model and no alterable variables, an optimal hydropower management strategy can be defined and transmitted. Likewise, this model will be periodically trained automatically considering past information together with the outcomes of proposed management strategies, thus learning every interaction. The final operational decision, for security reasons, will be of the hydropower manager or operator.

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[15] Around 1360 tagged fish between Guma and Vadocondes study sites. Pit-Tag technology is just for research interest as after will be replaced with a non-invasive fish counter.

Appendix 6. Focus on the European Union

In the European Union, hydropower plants have to comply with the requirements of several Directives: the Environmental Impact Assessment (EIA) Directive, the Habitats and Birds Directives (HD/BD) and the Water Framework Directive (WFD).[16] These Directives require the developers to identify and assess the significant environmental impacts and risks from such projects and propose relevant measures aiming to prevent and mitigate such impacts and risks. The competent authorities issue permits containing the necessary preventive and mitigation measures. If projects are likely to adversely affect Natura 2000 sites or water bodies, the competent authorities may still authorise such projects, provided that compensatory measures are implemented to address significant deterioration or damage and that the projects serve an overriding public interest. On the other hand, the recent measures proposed by the Commission (i.e. the RepowerEU proposal and the recently adopted Council Regulation laying down a framework to accelerate the deployment of renewable energy) presume that renewable energy projects are of overriding public interest. However, the competent authorities still have to properly identify and assess the impacts from hydropower projects and take the necessary measures to prevent, mitigate or compensate significant negative impacts. In addition to the above, when Member States seek EU co-financing under the Recovery and Resilience Facility (RRF), they have to comply with the Do No Significant Harm (DNSH) criteria to projects. The Regulation establishing the Recovery and Resilience Facility (RRF) provides that no measure included in a Recovery and Resilience Plan (RRP) should lead to significant harm to environmental objectives within the meaning of Article 17 (related to the DNSH principle) of the Taxonomy Regulation.

Environmental regulations aimed at mitigating the impacts of hydropower plants on the environment are currently unevenly enforced (Keith-Roach et al., 2016). The EU Water Framework Directive (WFD) objectives, and its two “daughter” directives, the Groundwater Directive (GWD) and Environmental Quality Standards Directive (EQSD) objectives, of achieving good chemical and ecological status of all surface and groundwater bodies, remain largely unachieved and related deadlines have been routinely extended (Kristensen et al., 2018). The main reasons for non-compliance could be due to the uncertainties with the definition of monitoring and assessment procedures and the lack of climate change adaptation strategies (European Commission, 2017a; Voulvoulis et al., 2017), thus should not be solely attributed to hydropower. The WFD is aimed at maintaining and improving the quality of aquatic ecosystems in the EU.

In the United States, the Clean Water Act from 1972 (EPA, 2002) similarly establishes the basic structure for regulating discharges of pollutants into the waters of the United States and regulating quality standards for surface waters. International standards have also been developed for those regions (in developing countries mostly) where such policies are not introduced strongly/yet, by the World Bank (2022) and the IHA (2022b).

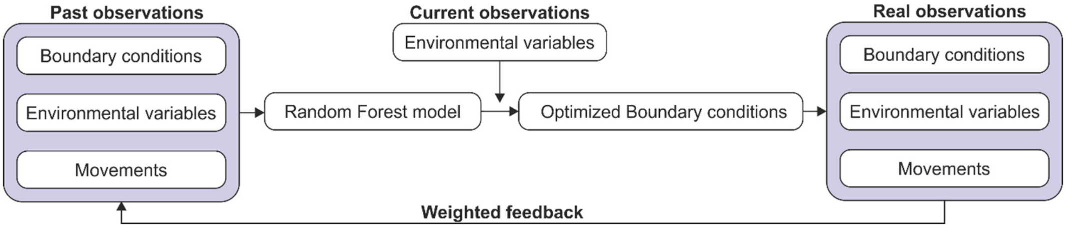

Fig. A3. Optimization of boundary conditions.

References

Achleitner, S., Rauch, W., 2007. Increase of river base flow by hydropower gate operation for mitigation of CSO impacts–potential and limitations. Water Resour. Manag. 21 (9), 1487–1503.

Ackermann, T., Loucks, D.P., Schwanenberg, D., Detering, M., 2000. Real-time modeling for navigation and hydropower in the river Mosel. J. Water Resour. Plan. Manag. 126 (5), 298–303.

Adam, B., Schwevers, U., 2006. The possibility of a eel protecting operation modus of hydropower plants with the early warning system MIGROMAT {sup registered}; Moeglichkeit eines aalschonenden Betriebs von Wasserkraftanlagen mit dem Fruehwarnsystem MIGROMAT {sup registered}. Wasserwirtschaft 96, 16–21.

Adamovic, M., Bisselink, B., De Felice, M., De Roo, A., Dorati, C., Ganora, D., Medarac, H., Pistocchi, A., Van De Bund, W., Vanham, D., 2019. Water-energy Nexus in Europe. In: Magagna, D., Bidoglio, G., Hidalgo Gonzalez, I., Peteves, E. (Eds.), EUR 29743 EN, Publications Office of the European Union, Luxembourg, 2019. ISBN: 978-92-76-03386-8 https://doi.org/10.2760/285180 JRC115853.

Almeida, R., Boavida, I., Pinheiro, A., 2017. Habitat modeling to assess fish shelter design under hydropeaking conditions. Can. J. Civ. Eng. 44 (2), 90–98.

Arcadis, 2010. Hydropower Generation in the Context of the WFD, Contract N° 070307/2010/574390/ETU/D1, Project N°11418.

Aswathi, J., Binojkumar, R.B., Oommen, T., Bouali, E.H., Sajinkumar, K.S., 2022. InSAR as a tool for monitoring hydropower projects: a review. Energy Geosci. 3 (2), 160–171.

Auer, S., Zeiringer, B., Fuhrer, S., Tonolla, D., Schmutz, S., 2017. Effects of river bank heterogeneity and time of day on drift and stranding of juvenile European grayling (Thymallus thymallus L.) caused by hydropeaking. Sci. Total Environ. 575, 1515–1521.

Auger, G., Ren, G., 2017. Reducing Maintenance with Water Lubricated Turbine Guide Bearings-Design Principles & Case Studies, Tribodays, 28–29 November 2017. Älvkarleby, Sweden.

Ausili, et al., 2022. Integrated sediment management guidelines and good practices in the context of the water framework directive. https://environment.ec.europa.eu/system/files/2022-09/CISdocumentsedimentfinalTO_BE_PUBLISHED_1430554724.pdf.

Barros, N., Cole, J.J., Tranvik, L.J., Prairie, Y.T., Bastviken, D., Huszar, V.L., ... Roland, F., 2011. Carbon emission from hydroelectric reservoirs linked to reservoir age and latitude. Nat. Geosci. 4 (9), 593–596.

Basnet, C.B., Panthi, K.K., 2018. Analysis of unlined pressure shafts and tunnels of selected Norwegian hydropower projects. Rock Mech. Geotech. Eng 10 (3), 486–512.

Batalla, R.J., Gibbins, C.N., Alcázar, J., Brasington, J., Buendia, C., Garcia, C., ... Vericat, D., 2021. Hydropeaked rivers need attention. Environ. Res. Lett. 16 (2), 021001.

Bauhofer, P., Zoglauer, M., 2021. Safeguarding climate targets: hydropower flexibility facilities. Chemie Ingenieur Technik 93 (4), 632–640.

Beeri, O., Peled, A., 2009. Geographical model for precise agriculture monitoring with real-time remote sensing. Photogramm. Remote Sensing 64 (1), 47–54.

Bejarano, M.D., Sordo-Ward, Á., Alonso, C., Jansson, R., Nilsson, C., 2020. Hydropeaking affects germination and establishment of riverbank vegetation. Ecol. Appl. 30 (4), e02076.

Belletti, B., Garcia de Leaniz, C., Jones, J., Bizzi, S., Börger, L., Segura, G., ... Zalewski, M., 2020. More than one million barriers fragment Europe’s rivers. Nature 588 (7838), 436–441.

Bently Nevada, 2022. https://dam.bakerhughesds.com/m/65bbcaf2f9e27e6a/original/BHCS13978-Hydro_Brochure_R2-pdf.pdf.

Betti, A., Crisostomi, E., Paolinelli, G., Piazzi, A., Ruffini, F., Tucci, M., 2021. Condition monitoring and predictive maintenance methodologies for hydropower plants equipment. Renew. Energy 171, 246–253.

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[16] The WFD requires surface water classification through the assessment of ecological status or ecological potential, and surface water chemical status. WFD Annex V explicitly defines the quality elements that must be used for the assessment of ecological status/potential. The lists of quality elements for each surface water category are subdivided into 3 groups: (1) biological elements; (2) hydromorphological elements supporting the biological elements; and (3) chemical and physical-chemical elements supporting the biological elements. The hydrological regime is part of the hydromorphological quality elements.

Bieri, M., Müller, M., Schweizer, S., Schleiss, A.J., 2014. Flow restoration in Alpine streams affected by hydropower operations-a case study for a compensation basin. Swiss Competences in River Engineering and Restoration: 7th International Conference on Fluvial Hydraulics. Taylor & Francis Books Ltd., pp. 181–190.

Bieri, M., Zünd, B., Gasser, M., Schleiss, A., 2016. Intervention Strategies to Mitigate Hydropeaking: Two Case Studies from Switzerland (No. CONF).

Bishwakarma, M.B., Støle, H., 2008. Real-time sediment monitoring in hydropower plants. Hydraul. Res. 46 (2), 282–288.

Blaas, H., Kroeze, C., 2016. Excessive nitrogen and phosphorus in European rivers: 2000–2050. Ecol. Indic. 67, 328–337.

Bock, N., Gökler, G., Reindl, R., Reingruber, J., Schmalfuß, R., Badura, H., ... Thöni, M.T., 2019. Feststoffmanagement bei Wasserkraftanlagen in Österreich. Österreichische Wasser-und Abfallwirtschaft 71 (3), 125–136.

Branche, E., 2017. The multipurpose water uses of hydropower reservoir: the SHARE concept. Comptes Rendus Physique 18 (7–8), 469–478.

Brandl, A., Laaha, G., Käfer, S., Mader, H., 2022. Key factors for the findability of fish passes in large Epipotamal Rivers: the case of the river Drava. Water 14 (10), 1530.

Bucur, D.M., Dunca, G., Bunea, F., Ciocan, G.D., 2019. Experimental analysis of the operation of a small Francis turbine equipped with an innovative aeration device. IOP Conference Series: Earth and Environmental Science. vol. 240 (4). IOP Publishing, p. 042010.

Bui, M.T., Kuzovlev, V.V., Zhenikov, Y.N., Füreder, L., Seidel, J., Schletterer, M., 2018. Water temperatures in the headwaters of the Volga River: trend analyses, possible future changes, and implications for a pan-European perspective. River Res. Appl. 34 (6), 495–505.

Bunea, F., Ciocan, G.D., Oprina, G., Băran, G., Băbuţanu, C.A., 2010. Hydropower impact on water quality. Environ. Eng. Manag. J. 9 (11).

Bunea, F., Ciocan, G.D., Bucur, D.M., Dunca, G., Nedelcu, A., 2021. Hydraulic turbine performance assessment with implementation of an innovative aeration system. Water 13 (18), 2459.

Bunt, C.M., Castro-Santos, T., Haro, A., 2012. Performance of fish passage structures at upstream barriers to migration. River Res. Appl. 28 (4), 457–478.

Capra, H., Plichard, L., Bergé, J., Pella, H., Ovidio, M., McNeil, E., Lamouroux, N., 2017. Fish habitat selection in a large hydropeaking river: strong individual and temporal variations revealed by telemetry. Sci. Total Environ. 578, 109–120.

Carolli, M., Maiolini, B., Bruno, M.C., Silveri, L., Siviglia, A., 2008. Thermopeaking in an hydropower impacted Alpine catchment. 4th ECRR conference on river restoration, Venice S. Servolo Island, Italy, pp. 789–796 June.

Carolli, M., et al., 2023. Impacts of existing and planned hydropower dams on river fragmentation in the Balkan region. Sci. Total Environ. 161940 (in press).

Cazzaniga, R., Rosa-Clot, M., 2021. The booming of floating PV. Sol. Energy 219, 3–10.

Cordova, M.M., Finardi, E.C., Ribas, F.A.C., De Matos, V.L., Scuzziato, M.R., 2014. Performance evaluation and energy production optimization in the real-time operation of hydropower plants. Electr. Power Syst. Res. 116, 201–207.

Creaco, E., Campisano, A., Fontana, N., Marini, G., Page, P.R., Walski, T., 2019. Real time control of water distribution networks: A state-of-the-art review. Water Res. 161, 517–530.

Crosa, G., Castelli, E., Gentili, G., Espa, P., 2010. Effects of suspended sediments from reservoir flushing on fish and macroinvertebrates in an alpine stream. Aquat. Sci. 72 (1), 85–95.

da Silva, T.M., Figueiredo, W.S., Zara, L.F., 2021. Hydraulic flow rate increase maneuver for ichthyofauna repulsion in bulb-type generating units–Jirau hydroelectric power plant. Periódico Eletrônico Fórum Ambiental da Alta Paulista 17 (4).

Delwiche, Kyle B., Harrison, John A., Maasakkers, Joannes D., Sulprizio, Melissa P., John, W., Jacob, Daniel J., Sunderland, Elsie M., 2022. Estimating driver and pathways for hydroelectric reservoir methane emissions using a new mechanistic model. J. Geophys. Res. Biogeosc. e2022JG006908.

Dickson, N.E., Carrivick, J.L., Brown, L.E., 2012. Flow regulation alters alpine river thermal regimes. J. Hydrol. 464, 505–516.

Dombrowsky, I., Hensengerth, O., 2018. Governing the water-energy-food nexus related to hydropower on shared rivers—the role of regional organizations. Front. Environ. Sci. 6, 153.

Doretto, A., Bo, T., Bona, F., Apostolo, M., Bonetto, D., Fenoglio, S., 2019. Effectiveness of artificial floods for benthic community recovery after sediment flushing from a dam. Environ. Monit. Assess. 191 (2), 1–12.

Dorfmann, C., Seidl, G., 2021. Ein neuer Ansatz zur Quantifizierung des fischökologischen Ausfallrisikos in schwallbeeinflussten Gewässerabschnitten. Wasserbau-Symposium 2021. Wasserbau in Zeiten von Energiewende, Gewässerschutz und Klimawandel. Band 2. 63, pp. 495–502.

DWA, 2005. Fischschutz- und Fischabstiegsanlagen – Bemessung, Gestaltung, Funktionskontrolle. 2. korrigierte Auflage Juli 2005. DWA-Themen, DWA – Deutsche Vereinigung für Wasserwirtschaft, Abwasser und Abfall e.V. (Hrsg.). pp. 1–256.

DWA, 2016. Merkblatt DWA-M 509 - Fischaufstiegsanlagen und fischpassierbare Bauwerke - Gestaltung, Bemessung, Qualitätssicherung - Mai 2014; Stand: korrigierte Fassung Februar 2016. https://webshop.dwa.de/de/merkblatt-dwa-m-509-mai-2014.html.

EPA, 2002. https://www.epa.gov/sites/default/files/2017-08/documents/federal-water-pollution-control-act-508full.pdf.

Espa, P., Brignoli, M.L., Crosa, G., Gentili, G., Quadroni, S., 2016. Controlled sediment flushing at the Cancano reservoir (Italian Alps): management of the operation and downstream environmental impact. J. Environ. Manag. 182, 1–12.

Falkenhem, R., Nakagawa, N., Havard, D., 2011. Technologies for eliminating oil in Kaplan-bulb turbines. Canals, tunnels and penstocks, europe, rehabilitation and repair. Technol. Equip. 6 (18).

Farhadi, A., Leitner, P., Graf, W., Hauer, C., 2022. Application of an unsteady three-dimensional computational fluid dynamics model to predictive habitat modelling of macroinvertebrates—A case study at the Ziller River in Austria. River Res. Appl. 38 (10), 1708–1720.

Felix, D., Albayrak, I., Abgottspon, A., Boes, R.M., 2016. Real-time measurements of suspended sediment concentration and particle size using five techniques. IOP Conference Series: Earth and Environmental Science. vol. 49 (12). IOP Publishing, p. 122006.

Felix, D., Albayrak, I., Abgottspon, A., Boes, R.M., 2016a. Hydro-abrasive erosion of hydraulic turbines caused by sediment-a century of research and development. IOP Conference Series: Earth and Environmental Science. vol. 49, 12. IOP Publishing, p. 122001.

Fellin, W., 2011. Abschätzung der Standsicherheit von annähernd unendlich langen Kriechhängen. Geotechnik 34 (1), 22–31. https://doi.org/10.1002/gete.201000018.

Feng, M., Zolezzi, G., Pusch, M., 2018. Effects of thermopeaking on the thermal response of alpine river systems to heatwaves. Sci. Total Environ. 612, 1266–1275.

Ferreira, A.R., Teegavarapu, R.S., 2012. Optimal and adaptive operation of a hydropower system with unit commitment and water quality constraints. Water Resour. Manag. 26 (3), 707–732.

Fjeldstad, H.P., Uglem, I., Diserud, O.H., Fiske, P., Forseth, T., Kvingedal, E., Hvidsten, N.A., ØKland, F., Järnegren, J., 2012. A concept for improving Atlantic salmon Salmo salar smolt migration past hydro power intakes. Fish Biol. 81, 642–663.

Fontana, N., Giugni, M., Glielmo, L., Marini, G., Zollo, R., 2019. Operation of a prototype for real time control of pressure and hydropower generation in water distribution networks. Water Resour. Manag. 33 (2), 697–712.

Fortum, 2022. Fishheart fishway has carried more than 12,500 fish over Fortum's Leppikoski hydropower plant. Online https://www.fortum.com/media/2022/08/fishheart-fishway-has-carried-more-12500-fish-over-fortums-leppikoski-hydropower-plant.

Fuentes-Pérez, J.F., Sanz-Ronda, F.J., de Azagra, A.M., García-Vega, A., 2016. Non-uniform hydraulic behavior of pool-weir fishways: A tool to optimize its design and performance. Ecol. Eng. 86, 5–12.

Fuentes-Pérez, J.F., García-Vega, A., Sanz-Ronda, F.J., de Azagra Paredes, A.M., 2017. Villemonte's approach: a general method for modeling uniform and non-uniform performance in stepped fishways. Knowl. Manag. Aquat. Ecosyst. 418, 23.

Free, G., Van De Bund, W., Gawlik, B., Van Wijk, L., Wood, M., Guagnini, E., Koutelos, K., Annunziato, A., Grizzetti, B., Vigiak, O., Gnecchi, M., Poikane, S., Christiansen, T., Whalley, C., Antognazza, F., Zerger, B., Hoeve, R., Stielstra, H., 2023. An EU analysis of the ecological disaster in the Oder River of 2022, EUR 31418 EN. Publications Office of the European Union, Luxembourg 978-92-76-99314-8 https://doi.org/10.2760/067386, JRC132271.

Fuentes-Pérez, J.F., Eckert, M., Tuhtan, J.A., Ferreira, M.T., Kruusmaa, M., Branco, P., 2018. Spatial preferences of Iberian barbel in a vertical slot fishway under variable hydrodynamic scenarios. Ecol. Eng. 125, 131–142.

Fuentes-Pérez, J.F., García-Vega, A., Bravo-Córdoba, F.J., Sanz-Ronda, F.J., 2021. A step to smart fishways: an autonomous obstruction detection system using hydraulic modeling and sensor networks. Sensors 21 (20), 6909.

García-Vega, A., Sanz-Ronda, F.J., Celestino, L.F., Makrakis, S., Leunda, P.M., 2018. Potamodromous brown trout movements in the north of the Iberian Peninsula: modelling past, present and future based on continuous fishway monitoring. Sci. Total Environ. 640, 1521–1536.

García-Vega, A., Fuentes-Pérez, J.F., Bravo-Córdoba, F.J., Ruiz-Legazpi, J., Valbuena-Castro, J., Sanz-Ronda, F.J., 2022. Pre-reproductive movements of potamodromous cyprinids in the Iberian Peninsula: when environmental variability meets semipermeable barriers. Hydrobiologia 849 (6), 1317–1338.

Garrido-Baserba, M., Corominas, L., Cortés, U., Rosso, D., Poch, M., 2020. The fourth-revolution in the water sector encounters the digital revolution. Environ. Sci. Technol. 54 (8), 4698–4705.

Gebre, S., Alfredsen, K., Lia, L., Stickler, M., Tesaker, E., 2013. Review of ice effects on hydropower systems. J. Cold Reg. Eng. 27 (4), 196–222.

Gebre, S., Timalsina, N., Alfredsen, K., 2014. Some aspects of ice-hydropower interaction in a changing climate. Energies 7 (3), 1641–1655.

Geist, J., 2021. Green or red: challenges for fish and freshwater biodiversity conservation related to hydropower. Aquat. Conserv. Mar. Freshwat. Ecosyst. 31 (7), 1551–1558.

Gómez, L., Niegowska, M., Navarro, A., Amendola, L., Arukwe, A., Ait-Aissa, S., ... Lettieri, T., 2021. Estrogenicity of chemical mixtures revealed by a panel of bioassays. Sci. Total Environ. 785, 147284.

González, D., Hanke, G., Tweehuysen, G., Bellert, B., Holzhauer, M., Palatinus, A., Hohenblum, P., Oosterbaan, L., 2016. Riverine litter monitoring - options and recommendations. MSFD GES TG marine litter thematic report; JRC technical report; EUR 28307.

González-Fernández, D., Cózar, A., Hanke, G., Viejo, J., Morales-Caselles, C., Bakiu, R., ... Tourgeli, M., 2021. Floating macrolitter leaked from Europe into the ocean. Nat. Sustain. 4 (6), 474–483.

Greimel, F., Neubarth, J., Fuhrmann, M., Führer, S., Habersack, H., Haslauer, M., Hauer, C., Holzapfel, P., Auer, S., Pfleger, M., Schmutz, S., Zeiringer, B., 2017. SuREmMa, Sustainable River Management - Energiewirtschaftliche und umweltrelevante Bewertung möglicher schwalldämpfender Maßnahmen. Forschungsbericht,Wien 92 pp https://info.bmlrt.gv.at/themen/wasser/gewaesserbewirtschaftung/forschungsprojekte/suremma.html.

Greimel, F., Schülting, L., Graf, W., Bondar-Kunze, E., Auer, S., Zeiringer, B., Hauer, C., 2018. Hydropeaking impacts and mitigation. Riverine ecosystem management 8, 91–110.

Grizzetti, B., Bouraoui, F., Aloe, A., 2012. Changes of nitrogen and phosphorus loads to E uropean seas. Glob. Chang. Biol. 18 (2), 769–782.

Grizzetti, B., Pistocchi, A., Liquete, C., Udias, A., Bouraoui, F., Van De Bund, W., 2017. Human pressures and ecological status of European rivers. Sci. Rep. 7 (1), 1–11.

Groß, J., 2014. Ökologische Durchgängigkeit der Mosel – Neubau einer Fischwechselanlage mit Monitoringstation sowie eines Besucher- Informationszentrums “Mosellum” an der Moselstaustufe in Koblenz. Korrespondenz Wasserwirtschaft 7 (2), 107–112.

Guangjie, P., Zhengwei, W., Yexiang, X., Yongyao, L., 2013. Abrasion predictions for Francis turbines based on liquid–solid two-phase fluid simulations. Engineering Failure Analysis 33, 327–335.

Haas, C., Thumser, P., Mockenhaupt, B., Schletterer, M., 2018. Das System Vaki-Riverwatcher als Möglichkeit für ein Langzeitmonitoring von Fisch-Migration in Fischaufstiegsanlagen. WasserWirtschaft 9, 41–48.

Habersack, H., Baranya, S., Holubova, K., Vartolomei, F., Skiba, H., Schwarz, U., ... Haimann, M., 2019. *Sediment manual for stakeholders*. Output 6.2 of the Interreg Danube transnational project. 241p https://www.interreg-danube.eu/approved-projects/danubesediment/outputs.

Hauer, C., Wagner, B., Aigner, J., Holzapfel, P., Flödl, P., Liedermann, M., … Habersack, H., 2018. State of the art, shortcomings and future challenges for a sustainable sediment management in hydropower: a review. Renew. Sust. Energ. Rev. 98, 40–55.

Halleraker, J.H., Natvik, E.V., Vaskinn, K., L'Abée-Lund, J.H., Alfredsen, K., 2023. By-pass valves in hydropower plants: An ecologically important measure to mitigate stranding in rivers due to emergency turbine flow shutdown. River Res. Applic. 1–14.

Hauer, C., Haimann, M., Holzapfel, P., Flödl, P., Wagner, B., Hubmann, M., … Schletterer, M., 2020. Controlled reservoir drawdown—challenges for sediment management and integrative monitoring: an Austrian case study—part A: reach scale. Water 12 (4), 1058.

Heggenes, J., Stickler, M., Alfredsen, K., Brittain, J.E., Adeva-Bustos, A., Huusko, A., 2021. Hydropower-driven thermal changes, biological responses and mitigating measures in northern river systems. River Res. Appl. 37 (5), 743–765.

Herdina, J., 2018. GKI hydroelectric power plant project: technical and contractual challenges. Tunnel 05 (2018), 48–56.

Hoffmann, T., Hillebrand, G., Schmegg, J., Vollmer, S., 2017. Monitoring long-term suspended sediment yields in Germaeny: quality controls on changing sediment sampling strategies. Proceedings of the IAHR: HydroSenSoft, international symposium and exhibition on hydro-environment sensors and software. Madrid, 1-3 March 2017, pp. 1–7.

Huang, H., Chen, B., 2012. Dam seepage monitoring model based on dynamic effect weight of reservoir water level. Energy Procedia 16, 159–165.

Hubmann, M., Schletterer, M., 2016. Development of a habitat preference curve for the mayfly *Baetis alpinus* (Pictet 1843). Zoosymposia 11, 65–72.

Hülsmann, S., Rinke, K., Paul, L., Santos, C.D., 2021. Storage reservoir operation and management. Handbook of Water Resources Management: Discourses, Concepts and Examples, pp. 777–799.

I AM HYDRO, G, 2022. I AM HYDRO GmbH. Von. https://iamhydro.com/downloads/i-am-hydro_flyer_hydrocam_2021_en.pdf.

IHA, 2022. Hydropower sustainability guidelines. https://www.hydropower.org/publications/hydropower-sustainability-guidelines.

International Hydropower Association (IHA), 2022. Hydropower Status Report Sector Trends and Insights. IHA Central Office, United Kingdom.

Jager, H.I., Smith, B.T., 2008. Sustainable reservoir operation: can we generate hydropower and preserve ecosystem values? River Res. Appl. 24 (3), 340–352.

Jiménez, O.F., Chaudhry, M.H., 1992. Water-level control in hydropower plants. Energy Eng. 118 (3), 180–193.

Keith-Roach, M., Grundfelt, B., Höglund, L.O., Kousa, A., Pohjolainen, E., Magistrati, P., … Ferrari, A., 2016. Environmental legislation and best practice in the emerging European rare earth element industry. Rare Earths Industry 279–291.

Kemenes, A., Forsberg, B.R., Melack, J.M., 2007. Methane release below a tropical hydroelectric dam. Geophys. Res. Lett. 34 (12).

Kikuchi, R., do Amaral, P.B., 2008. Conceptual schematic for capture of biomethane released from hydroelectric power facilities. Bioresour. Technol. 99 (13), 5967–5971.

Kitchen, N.R., 2008. Emerging technologies for real-time and integrated agriculture decisions. Comput. Electron. Agric. 61 (1), 1–3.

Kopecki, I., Schneider, M., Tuhtan, J.A., Ortlepp, J., Thonhauser, S., Schletterer, M., 2016. Leitströmung an Fischaufstiegshilfen: Bewertung und Optimierung mit Hilfe eines ethohydraulischen Ansatzes. WasserWirtschaft 10, 37–42.

Kopecki, I., Schneider, M., Schletterer, M., 2022. Modelling of habitat changes related to hydropeaking with CASiMiR. Novel Developments for Sustainable Hydropower. Springer, Cham, pp. 147–156.

Kougias, I., Aggidis, G., Avellan, F., Deniz, S., Lundin, U., Moro, A., … Theodossiou, N., 2019. Analysis of emerging technologies in the hydropower sector. Renew. Sust. Energ. Rev. 113, 109257.

Kristensen, P., Whalley, C., Zal, F. N. N., & Christiansen, T. (2018). European waters assessment of status and pressures 2018. *EEA Report*, (7/2018).

Kuriqi, A., Pinheiro, A.N., Sordo-Ward, A., Garrote, L., 2020. Water-energy-ecosystem nexus: balancing competing interests at a run-of-river hydropower plant coupling a hydrologic–ecohydraulic approach. Energy Convers. Manag. 223, 113267.

Leitner, P., Hauer, C., Graf, W., 2017. Habitat use and tolerance levels of macroinvertebrates concerning hydraulic stress in hydropeaking rivers–a case study at the Ziller River in Austria. Sci. Total Environ. 575, 112–118.

Liedermann, M., Gmeiner, P., Pessenlehner, S., Haimann, M., Hohenblum, P., Habersack, H., 2018. A methodology for measuring microplastic transport in large or medium rivers. Water 10 (4), 414.

Liedermann, M., Rindler, R., Aigner, J., Kreisler, A., Glock, K., Pessenlehner, S., Kloesch, M., Habersack, H., 2019. Research on alpine sediment processes, morphodynamics and ecosystem behaviour considering extreme events. 38th IAHR World Congress https://doi.org/10.3850/38WC092019-1637.

Lindim, C., Van Gils, J., Georgieva, D., Mekenyan, O., Cousins, I.T., 2016. Evaluation of human pharmaceutical emissions and concentrations in Swedish river basins. Sci. Total Environ. 572, 508–519.

Liu, X., Xiao, S., Pan, H., Zheng, X., Han, W., Huang, C., Deng, S., 2022. Optimizing hydropower plants based on carbon-water-energy-ecosystem nexus. Energy Convers. Manag. 270, 116191.

Maavara, T., Parsons, C.T., Ridenour, C., Stojanovic, S., Dürr, H.H., Powley, H.R., Van Cappellen, P., 2015. Global phosphorus retention by river damming. Proc. Natl. Acad. Sci. 112 (51), 15603–15608.

Mader, H., Käfer, S., 2020. FishCam & FishNet–fischökologisches monitoring 4.0. Österreichische Wasser-und Abfallwirtschaft 72 (3), 129–141.

Mader, H., Käfer, S., Kratzert, F., 2017a. FishCam – Videomonitoring zur Funktionsanalyse von Fischaufstiegsanlagen. WasserWirtschaft. 2017 (2–3), S59–S64.

Mader, H., Käfer, S., Kratzert, F., 2017b. FishCam – Videomonitoring zur Funktionsanalyse von Fischaufstiegsanlagen. WasserWirtschaft. 2017 (2–3), S59–S64.

Mader, H., Brandl, A., Kaefer, S., 2020. Design and function monitoring of an Enature® vertical slot fish pass in a large Potamal River in Carinthia/Austria. Water 12 (2), 551.

Majumder, P., Majumder, M., Saha, A.K., Sarkar, K., Nath, S., 2019. Real time reliability monitoring of hydro-power plant by combined cognitive decision-making technique. Int. Energy Res. 43 (9), 4912–4939.

Mekonnen, M.M., Hoekstra, A.Y., 2012. The blue water footprint of electricity from hydropower. Hydrol. Earth Syst. Sci. 16 (1), 179–187.

Miasayedava, L., McBride, K., Tuhtan, J.A., 2022. Automated environmental compliance monitoring of rivers with IoT and open government data. Environ. Manag. 303, 114283.

Moreira, M., Hayes, D.S., Boavida, I., Schletterer, M., Schmutz, S., Pinheiro, A., 2019. Ecologically-based criteria for hydropeaking mitigation: a review. Sci. Total Environ. 657, 1508–1522.

Moreira, M., Schletterer, M., Quaresma, A., Boavida, I., Pinheiro, A., 2020. New insights into hydropeaking mitigation assessment from a diversion hydropower plant: the GKI project (Tyrol, Austria). Ecol. Eng. 158, 106035.

Müller, M., Keller, Y., Billeter, P., Kaderli, R., Gehri, M., Kost, M., 2016. Hydropeaking Mitigation Measures-Planning, Realization and Operation of the First Swiss Hydropeaking Compensation Basin in Innertkirchen BE.

Negm, A., Ma, X., Aggidis, G., 2023. Review of leakage detection in water distribution networks. IOP Conf. Ser.: Earth Environ. Sci. 1136, 012052.

Nguyen, T.H.T., Everaert, G., Boets, P., Forio, M.A.E., Bennetsen, E., Volk, M., … Goethals, P.L., 2018. Modelling tools to analyze and assess the ecological impact of hydropower dams. Water 10 (3), 259.

Nielsen, N., Szabo-Meszaros, M. (Eds.), 2022. A Roadmap for Best Practice Management – IEA Hydro report on Annex XIII Hydropower and Fish 150 pp.

Økland, F., Teichert, M.A.K., Havn, T. B., Thorstad, E.B., Heermann, L., Sæther, S. A., Tambets, M., and Borcherding, J. Downstream migration of European eel at three German hydropower stations. Nina Report, 1355: (53 pages).

Olofintoye, O., Otieno, F., Adeyemo, J., 2016. Real-time optimal water allocation for daily hydropower generation from the Vanderkloof dam, South Africa. Appl. Soft Comput. 47, 119–129.

ÖWAV, 2020. ÖWAV-Arbeitsbehelf 56: Wartung von Fischaufstiegshilfen. 40 pp https://www.oewav.at/Publikationen?current=391388&mode=form.

Pacheco, F.S., Soares, M.C.S., Assireu, A.T., Curtarelli, M.P., Roland, F., Abril, G., … Ometto, J.P., 2015. The effects of river inflow and retention time on the spatial heterogeneity of chlorophyll and water–air CO 2 fluxes in a tropical hydropower reservoir. Biogeosciences 12 (1), 147–162.

Palmieri, A., Shah, F., Dinar, A., 2001. Economics of reservoir sedimentation and sustainable management of dams. J. Environ. Manag. 61 (2), 149–163.

Parasiewicz, P., 2007. Using MesoHABSIM to develop reference habitat template and ecological management scenarios. River Res. Appl. 23, 924–932.

Parasiewicz, P., 2008. Application of mesohabsim and target fish community approaches for selecting restoration measures of the Quinebaug River, Connecticut and Massachusetts, USA. River Res. Appl. 24, 459–471.

Pérez-Díaz, J.I., Millan, R., Garcia, D., Guisandez, I., Wilhelmi, J.R., 2012. Contribution of re-regulation reservoirs considering pumping capability to environmentally friendly hydropower operation. Energy 48 (1), 144–152.

Person, E., Bieri, M., Peter, A., Schleiss, A.J., 2014. Mitigation measures for fish habitat improvement in Alpine rivers affected by hydropower operations. Ecohydrology 7 (2), 580–599.

Peters, N.E., Meybeck, M., Chapman, D.V., 2006. Effects of Human Activities on Water Quality. Encyclopedia of Hydrological Sciences.

Peterson, M.J., Cada, G.F., Sale, M.J., Eddlemon, G.K., 2003. Regulatory Approaches for Addressing Dissolved Oxygen Concerns at Hydropower Facilities. EERE Publication and Product Library, Washington, DC (United States).

Peterson, M.L., Fuller, A.N., Demko, D., 2017. Environmental factors associated with the upstream migratory activity of fall-run Chinook salmon in a regulated river. N. Am. J. Fish Manag. 37.

Peteuil, C., Frétaud, T., Wirz, C., Camenen, B., Guertault, L., Le Coz, J., Dramais, G., 2014. Importance of field observation for managing sediment fluxes in hydropower projects design and operation. Proceedings of the 19th IAHR-APD Congress.

Pighini, S., Ventura, M., Miglietta, F., Wohlfahrt, G., 2018. Dissolved greenhouse gas concentrations in 40 lakes in the Alpine area. Aquat. Sci. 80 (3), 1–13.

Pisaturo, Giuseppe Roberto, 2017. Protection Infrastructures and Methods for Reducing the Impacts Downstream of Hydropower Plants. PhD thesis,University of Trento.

Pleizier, N.K., Nelson, C., Cooke, S.J., Brauner, C.J., 2020. Understanding gas bubble trauma in an era of hydropower expansion: how do fish compensate at depth? Can. J. Fish. Aquat. Sci. 77 (3), 556–563.

Popa, B., Popa, F., Tică, E.I., Neagoe, A., Diminescu, M.A., 2019. Retention basin with Golesti SHPP downstream dam for mitigating hydropeaking and producing green electricity. E3S Web of Conferences. vol. 85. EDP Sciences, p. 06011.

Prairie, Y.T., Mercier-Blais, S., Harrison, J.A., Soued, C., del Giorgio, P., Harby, A., … Nahas, R., 2021. A new modelling framework to assess biogenic GHG emissions from reservoirs: the G-res tool. Environ. Model Softw. 143, 105117.

Praveen, K.R., Chophel, J., Wangchuk, J., Tshewang, K., Bansal, N.C., 2022. IBIS-FM radar as a tool for monitoring hill slopes during excavations in hydropower projects: a case study from Bhutan Himalayas. Energy Geosci. 3 (2), 211–217.

Premstaller, G., Cavedon, V., Pisaturo, G.R., Schweizer, S., Adami, V., Righetti, M., 2017. Hydropeaking mitigation project on a multi-purpose hydro-scheme on Valsura River in South Tyrol/Italy. Sci. Total Environ. 574, 642–653.

Pulg, U., Stranzl, S., Wagner, B., et al., 2020. Gasübersättigung in Flüssen? Messung, Ursachen und Auswirkungen – Ein internationales Forschungsprojekt untersucht Verbreitung und Umwelteffekte. Österr Wasser- und Abfallw 72, 142–148.

Quaranta, 2023. Lubricant oil consumption and opportunities for oil-free turbines in the hydropower sector: a European assessment. Energies 16 (2), 834.

Quaranta, E., Davies, P., 2021. Emerging and innovative materials for hydropower engineering applications: turbines, bearings, sealing, dams and waterways, and ocean power. Engineering 8, 148–158.

Quaranta, E., Hunt, J., 2022. Retrofitting and refurbishment of hydropower plants: case studies and novel technologies. Renewable Energy Production and Distribution. Academic Press, pp. 301–322.

Quaranta, E., Muntean, S., 2023. Wasted and excess energy in the hydropower sector: a European assessment of tailrace hydrokinetic potential, degassing-methane capture and waste-heat recovery. Appl. Energy 329, 120213.

Quaranta, E., Trivedi, C., 2021. The state-of-art of design and research for Pelton turbine casing, weight estimation, counterpressure operation and scientific challenges. Heliyon 7 (12), e08527.

Quaranta, E., Bonjean, M., Cuvato, D., Nicolet, C., Dreyer, M., Gaspoz, A., ... Bragato, N., 2020. Hydropower case study collection: innovative low head and ecologically improved turbines, hydropower in existing infrastructures, hydropeaking reduction, digitalization and governing systems. Sustainability 12 (21), 8873.

Quaranta, E., Aggidis, G., Boes, R.M., Comoglio, C., De Michele, C., Patro, E.R., ... Pistocchi, A., 2021. Assessing the energy potential of modernizing the European hydropower fleet. Energy Convers. Manag. 246, 114655.

Quaranta, E., Pérez-Díaz, J.I., Romero-Gomez, P., Pistocchi, A., 2021a. Environmentally enhanced turbines for hydropower plants: current technology and future perspective. Front. Energy Res. 592.

Quaranta, E., Fuchs, S., Liefting, H.J., Schellart, A., Pistocchi, A., 2022a. Costs and benefits of combined sewer overflow management strategies at the European scale. J. Environ. Manag. 318, 115629.

Quaranta, E., Georgakaki, A., Letout, S., Kuokkanen, A., Mountraki, A., Ince, E., ... Grabowska, M., 2022b. Clean Energy Technology Observatory: Hydropower and Pumped Hydropower Storage in the European Union–2022 Status Report on Technology Development. Trends, Value Chains and Markets.

Rai, A.K., Kumar, A., Hies, T., Nguyen, H.H., 2016. Field application of a multi-frequency acoustic instrument to monitor sediment for silt erosion study in Pelton turbine in Himalayan region, India. IOP Conference Series: Earth and Environmental Science. vol. 49, 12. IOP Publishing, p. 122004.

Reindl, R., Neuner, J., Schletterer, M., 2022. Increased hydropower production and hydropeaking mitigation along the upper Inn River (Tyrol, Austria) with a combination of buffer reservoirs, diversion hydropower plants and retention basins. River Res. Applic.

Reuther, Kristof Maria, 2022. Migration of the Lake-Run Brown Trout (*Salmo trutta*) in the Hasliaare River under Special Consideration of Discharge and Water Depth. Master Thesis at BOKU-Universität für Bodenkultur, p. 97.

Rutschmann, P., Kampa, E., Wolter, C., Albayrak, I., David, L., Stoltz, U., Schletterer, M., 2022. Novel Developments for Sustainable Hydropower.

Saadatpour, M., Javaheri, S., Afshar, A., Solis, S.S., 2021. Optimization of selective withdrawal systems in hydropower reservoir considering water quality and quantity aspects. Expert Syst. Appl. 184, 115474.

Salalila, A., Martinez, J., Elsinghorst, R., Hou, H., Yuan, Y., Deng, Z.D., 2020. Real-time and autonomous water quality monitoring system based on remotely operated vehicle. Global Oceans 2020: Singapore–US Gulf Coast. IEEE, pp. 1–5.

Salmaso, F., Servanzi, L., Crosa, G., Quadroni, S., Espa, P., 2021. Assessing the impacts of hydropeaking on river benthic macroinvertebrates: a state-of-the-art methodological overview. Environments 8 (7), 67.

Sarasúa, J.I., Fraile-Ardanuy, J., Perez, J.I., Wilhelmi, J.R., Sanchez, J.A., 2007. Control of a run of river small hydro power plant. 2007 International Conference on Power Engineering, Energy and Electrical Drives. IEEE, pp. 672–677 April.

Sarasúa, J.I., Elías, P., Martínez-Lucas, G., Pérez-Díaz, J.I., Wilhelmi, J.R., Sánchez, J.Á., 2014. Stability analysis of a run-of-river diversion hydropower plant with surge tank and spillway in the head pond. Sci. World J. 2014.

Schaanning, M., Rundberget, T., Jenssen, M.T.S., 2020. Bioavailability and Bioaccumulation of Perfluorinated Compounds (PFAS) in a Polluted River Sediment (NIVA-rapport).

Scherer, L., Pfister, S., 2016. PloS one 11 (9) Hydropower's biogenic carbon footprint. e0161947.

Schilt, C.R., 2007. Developing fish passage and protection at hydropower dams. Appl. Anim. Behav. Sci. 104 (3–4), 295–325.

Schleiss, A.J., Franca, M.J., Juez, C., De Cesare, G., 2016. Reservoir sedimentation. J. Hydraul. Res. 54 (6), 595–614. https://doi.org/10.1080/00221686.2016.1225320.

Schletterer, M., Senn, G., Menghin, M., Hubmann, M., Schwarzenberger, R., Haas, C., ... Asgeirsson, M.T., 2015. Technisches Fischmonitoring: installation des ersten Riverwatcher Fischzählers in Österreich. Wasserwirtschaft 7 (8), 103–108.

Schletterer, M., Reindl, R., Thonhauser, T., 2016. Options for re-establishing river continuity, with an emphasis on the special solution “fish lift”: examples from Austria. Revista Eletrônica de Gestão e Tecnologias Ambientais (GESTA) 4 (1), 109–128.

Schmidt, M.B., Tuhtan, J.A., Schletterer, M., 2018. Hydroacoustic and pressure turbulence analysis for the assessment of fish presence and behavior upstream of a vertical trash rack at a run-of-river hydropower plant. Appl. Sci. 8 (10), 1723.

Schmutz, S., Bakken, T.H., Friedrich, T., Greimel, F., Harby, A., Jungwirth, M., Melcher, A., Unfer, G., Zeiringer, B., 2015. Response of fish communities to hydrological and morphological alterations in hydropeaking Rivers of Austria. River Res. Appl. 31, 919–930.

Shin, J.K., Park, Y., Kim, N.Y., Hwang, S.J., 2022. Downstream transport of Geosmin based on harmful cyanobacterial outbreak upstream in a reservoir Cascade. Int. J. Environ. Res. Public Health 19 (15), 9294.

Smith, B.T., Jager, H.I., March, P., 2007. Prospects for Combining Energy and Environmental Objectives in Hydropower Optimization. Waterpower XI.

Sollberger, S., Wehrli, B., Schubert, C.J., DelSontro, T., Eugster, W., 2017. Minor methane emissions from an Alpine hydropower reservoir based on monitoring of diel and seasonal variability. Environ Sci Process Impacts 19 (10), 1278–1291.

Soom, J., Pattanaik, V., Leier, M., Tuhtan, J.A., 2022. Environmentally adaptive fish or no-fish classification for river video fish counters using high-performance desktop and embedded hardware. Ecol. Inform. 101817.

Sorkhabi, O.M., Shadmanfar, B., Kiani, E., 2022. Monitoring of dam reservoir storage with multiple satellite sensors and artificial intelligence. Results in Engineering. 16, p. 100542.

St. Germain, F., 2018. Addressing Pressure Loss and Oil Leakage in Kaplan-Bulb Turbines and the Impact on Efficiency. BBA, Mont-Saint-Hilaire, Québec, Canada.

Sun, J., Zhang, Y., Liu, B., Ge, X., Zheng, Y., Fernandez-Rodriguez, E., 2022. Research on oil mist leakage of bearing in Hydropower Station: a review. Energies 15 (7), 2632.

Teegavarapu, R.S., Ferreira, A.R., Simonovic, S.P., 2013. Fuzzy multiobjective models for optimal operation of a hydropower system. Water Resour. Res. 49 (6), 3180–3193.

Teichert, N., Tétard, S., Trancart, T., Feunteun, E., Acou, A., de Oliveira, E., 2020. Resolving the trade-off between silver eel escapement and hydropower generation with simple decision rules for turbine shutdown. J. Environ. Manag. 261, 110212.

Tétard, S., Roy, R., Teichert, N., Rancon, J., Courret, D., 2021. Temporary turbine and reservoir level management to improve downstream migration of juvenile salmon through a hydropower complex. Knowl. Manag. Aquat. Ecosyst. 422, 4.

Thonhauser, S., Oberwalder, M., Mühlbacher, F., Frick, E., Gracner, R., Schletterer, M., 2017. Fischlift Runserau – eine innovative Lösung für schwierige Standorte. WasserWirtschaft 2-3, 20–26.

Tonolla, D., Bruder, A., Schweizer, S., 2017. Evaluation of mitigation measures to reduce hydropeaking impacts on river ecosystems–a case study from the Swiss Alps. Sci. Total Environ. 574, 594–604.

Tuhtan, J.A., Fuentes-Perez, J.F., Angerer, T., Schletterer, M., 2018. Monitoring upstream fish passage through a bypass pipe and drop at the fish lift Runserau: comparing dynamic pressure measurements on live fish with passive electronic fish surrogates. International Symposium on Ecohydraulics.

Valbuena-Castro, J., Fuentes-Pérez, J.F., García-Vega, A., Bravo-Córdoba, F.J., Ruiz-Legazpi, J., de Azagra Paredes, A.M., Sanz-Ronda, F.J., 2020. Coarse fishway assessment to prioritize retrofitting efforts: a case study in the Duero River basin. Ecol. Eng. 155, 105946.

van Emmerik, T., Mellink, Y., Hauk, R., Waldschläger, K., Schreyers, L., 2022. Rivers as plastic reservoirs. Front. Water 3, 1–8.

Vanham, D., Medarac, H., Schyns, J.F., Hogeboom, R.J., Magagna, D., 2019. The consumptive water footprint of the European Union energy sector. Environ. Res. Lett. 14 (10), 104016.

Värlind, K.-E., 2002. Oil-free operation. Water Power and Dam Construction.

Vassoney, E., Mammoliti Mochet, A., Rocco, R., Maddalena, R., Vezza, P., Comoglio, C., 2019. Integrating meso-scale habitat modelling in the multicriteria analysis (MCA) process for the assessment of hydropower sustainability. Water 11 (4), 640.

Vassoney, E., Mammoliti Mochet, A., Comoglio, C., 2020. Multicriteria analysis for the assessment of flow release scenarios from a hydropower plant in the Alpine region. Water Resour. Manag. 34 (2), 637–651.

Vassoney, E., Mammoliti Mochet, A., Desiderio, E., Negro, G., Pilloni, M.G., Comoglio, C., 2021. Comparing multi-criteria decision-making methods for the assessment of flow release scenarios from small hydropower plants in the alpine area. Front. Environ. Sci. 9, 635100.

Vezza, P., Parasiewicz, P., Spairani, M., Comoglio, C., 2014. Habitat modeling in high-gradient streams: the mesoscale approach and application. Ecol. Appl. 24 (4), 844–861.

Vezza, P., Goltara, A., Spairani, M., Zolezzi, G., Siviglia, A., Carolli, M., ... Parasiewicz, P., 2015. Habitat indices for rivers: quantifying the impact of hydro-morphological alterations on the fish community. Engineering Geology for Society and Territory-Volume. 3, pp. 357–360.

Vigiak, O., Grizzetti, B., Udias-Moinelo, A., Zanni, M., Dorati, C., Bouraoui, F., Pistocchi, A., 2019. Predicting biochemical oxygen demand in European freshwater bodies. Sci. Total Environ. 666, 1089–1105.

Voulvoulis, N., Arpon, K.D., Giakoumis, T., 2017. The EU water framework directive: from great expectations to problems with implementation. Sci. Total Environ. 575, 358–366.

Voutchkov, N., 2019. II. Disruptive innovations in the water sector. The Future of Water. 14.

Vuyovich, C.M., Daly, S.F., Gagnon, J.J., Weyrick, P., Zaitsoff, M., 2009. Monitoring river ice conditions using web-based cameras. Cold Reg. Eng. 23 (1), 1–17.

Vyshnevskyi, V.I., 2020. Temperature and ice regimes of waterbodies under the impacts of global warming and a hydropower plant. Meteorology Hydrology and Water Management. Research and Operational Applications, p. 8.

Wagner, F., et al., 2022. A new, non-invasive fish backpack biologger to measure the physical conditions experienced by swimming fish during downstream passage. Fish Passage 2022.

Walsh, J.T., Prien, D.M., 1995. Penstock Leak Detection Using Accurate Flow Monitoring Systems (No. CONF-9507190-). American Society of Civil Engineers, New York, NY (United States).

Wang, H., Liu, X., Ma, L., Zhang, Y., 2021. Anomaly detection for hydropower turbine unit based on variational modal decomposition and deep autoencoder. Energy Rep. 7, 938–946.

Wang, X., Alsaleh, M., Abdul-Rahim, A.S., 2022. The role of information and communication technologies in achieving hydropower sustainability: evidence from European Union economies. Energy Environ. 0958305X221137566.

Wardlaw, R.B., Sharif, M., Kimaite, F., 2005. Real-time hydro-power forecasting on the Victoria Nile. Proceedings of the Institution of Civil Engineers-Water Management. 158, 2. Thomas Telford Ltd, pp. 45–54.

Water Framework Directive, 2014. Ecological Flows in the Implementation of the Water Framework Directive. CIS guidance document no. 31.

Watkins, L., McGrattan, S., Sullivan, P.J., Walter, M.T., 2019. The effect of dams on river transport of microplastic pollution. Sci. Total Environ. 664, 834–840.

WDFW, 2000. Fish Protection Screen Guidelines for Washington State (Draft). Washington Department of Fish and Wildlife 56 pp.

Weitkamp, D.E., Katz, M., 1980. A review of dissolved gas supersaturation literature. Trans. Am. Fish. Soc. 109 (6), 659–702.

World Bank, 2022. Hydroelectric power: a guide for developers and investors (worldbank.org). https://openknowledge.worldbank.org/handle/10986/22788.

Xiao, S.B., Liu, W.G., Yang, H., Liu, D., Wang, Y., Peng, F., 2015. Extreme methane bubbling emissions from a subtropical shallow eutrophic pond. Austin Biom. Biostat. 1, 1–6.

Yang, Y., Lu, J., Pflugrath, B.D., Li, H., Martinez, J.J., Regmi, S., ... Deng, Z.D., 2021. Lab-on-a-Fish: wireless, miniaturized, fully integrated, implantable biotelemetric tag for real-time in vivo monitoring of aquatic animals. IEEE Internet Things 9 (13), 10751–10762.

Yang, Y., Elsinghorst, R., Martinez, J.J., Hou, H., Lu, J., Deng, Z.D., 2022. A real-time underwater acoustic telemetry receiver with edge computing for studying fish behavior and environmental sensing. IEEE Internet Things J. 9 (18), 17821–17831.

Yapa, P.D., Shen, H.T., 1984. Effect of ice cover on hydropower production. J. Energy Eng. 110 (3), 231–234.

Yin, T., Zang, X., Hou, Z.J., Jacobson, P., Mueller, R., Deng, Z., 2020. Bridging the Gap between Laboratory and Field Experiments in American Eel Detection Using Transfer Learning and Convolutional Neural Network.

Zang, X., Yin, T., Hou, Z., Mueller, R.P., Deng, Z.D., Jacobson, P.T., 2021. Deep learning for automated detection and identification of migrating American eel Anguilla rostrata from imaging sonar data. Remote Sens. 13 (14), 2671.

Zhang, C., Liu, N., Hong, J., Buyue, Y., 2021. Design of seepage control system around a large-scale underground powerhouse: a case study of Baihetan Hydropower Station. IOP Conference Series: Earth and Environmental Science. vol. 861, 7. IOP Publishing, p. 072074.

Zhao, Y., Liu, S., Shi, H., 2021. Impacts of dams and reservoirs on local climate change: a global perspective. Environ. Res. Lett. 16 (10), 104043.

Zolezzi, G., Siviglia, A., Toffolon, M., Maiolini, B., 2011. Thermopeaking in Alpine streams: event characterization and time scales. Ecohydrology 4 (4), 564–576.