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Multicomponent assessment of the impact of hydropower cascade on fish metrics

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HIGHLIGHTS

- Research fulfils the lack of studies on understanding of HPPs interaction in hydropower cascade.
- Expands perception of the impact of hydropower cascade on hydrologic alterations and fish metrics as ecological indicators.
- HPP multimetric approach was proposed for the assessment of the integrated impact of each HPP in the hydropower cascade.

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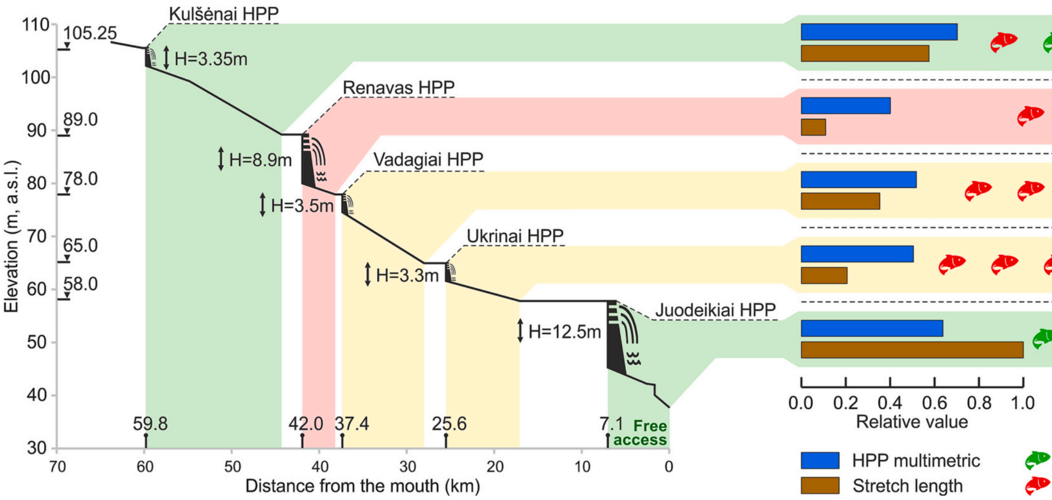
GRAPHICAL ABSTRACT



ABSTRACT

The water sector is one of the priority areas of the European Union; therefore, legislation encourages the development of methods to protect the river ecosystem. The key to this is the characterization of the river's physical features with respect to ecological quality. Rivers are a complex system in which geomorphic conditions, hydrological regime, and ecological indicators interact. The group of hydropower plants (HPPs) that forms a hydropower cascade disturbs the natural continuity of river system components. Analysis of the spatial and temporal alterations in the river environment is important for understanding the potential impact of the hydropower cascade on ecological indicators. In a current study, the multicomponent assessment was used to

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Fish habitats
Fish metrics

evaluate the impact of the hydropower cascade of five HPPs on fish metrics as ecological indicators in the case study Varduva River. The research involved field surveys to collect hydrological data in highly affected ungauged river to estimate indicators of hydrologic alterations under HPPs operation, use of Unmanned Aerial Vehicles and digital photogrammetry to map geomorphic units, fish sampling to estimate composition of fish species and guilds, and fish habitat availability modelling based on the collected data and the conditional habitat suitability criteria using the MesoHABSIM modelling approach. Results revealed that the technical characteristics of HPPs determined their individual operation mode, which had a crucial impact on the hydrologic alterations of the river and, together with the distance between the dams, on the variation of fish metrics in the hydropower cascade. The intensive operation of the hydropower cascade created adverse effects for intolerant fish but was advantageous for tolerant fish species. The proposed HPP multimetric correlated with the fish metrics and showed similar tendencies between HPPs as habitat integrity index (IH), derived from MesoHABSIM modelling.

1. Introduction

Construction of dams is considered a major factor that significantly modifies river ecosystems. It comes together with severe ecological, economic, and social impacts. In many developed countries, well-established legislation and directives, e.g., in the EU, Water Framework Directive (WFD) 2000/60/EC, require that the planning, development, and operation of such dam construction guarantee a “good” ecological status of the river under exploitation (Directive 2000/60/EC; Kallis and Butler, 2001). There are many types of research on the downstream impacts of dams at the regional or basin scale (Couto and Olden, 2018; Athayde et al., 2019) and downstream impacts on habitat conditions (Mbaka and Wanjiru Mwaniki, 2015) because ecosystem degradation occurs more often downstream from a dam. Also, scientists evaluated the impact of small hydropower on the environment and society (Kelly-Richards et al., 2017; Shiji et al., 2021), as well as on the specific fish species (Gibeau et al., 2017; Virbickas et al., 2020; Akstinas et al., 2021; Kuriqi et al., 2021), and basin-scale ecological impacts of Small Hydropower Plants (Lange et al., 2018).

The natural flow regime is an important driver for biological processes that guarantee the ecological vitality of the aquatic habitat (Poff, 2018). Therefore, inappropriate usage of water resources might significantly influence the integrity of the fluvial ecosystems (Mittal et al., 2016). Maintaining close to natural hydrological conditions in technical structures may cause less negative ecological effect. Therefore, the environmental flow is one of the key management tools to restore river ecosystems (Yue et al., 2021).More than two hundred methods for assessing environmental flows have been described in scientific research (Tharme, 2003). These methods can be generally classified into four main categories: hydrological, hydraulic, habitat simulation, and holistic (Tharme, 2003; Acreman and Dunbar, 2004; Petts, 2009; Acreman et al., 2014). The hydrological methods are still the most widely and internationally used. They could be described as a simple, rapid, inexpensive way to provide information that does not necessarily require as much fieldwork as other methods. But at the same time, these methods offer low-resolution output and absent or limited direct ecological links compared with habitat simulation methodologies. The latter have high-resolution habitat-flow relationships, generation of alternative flow scenarios, and focus on target species (Acreman and Dunbar, 2004; Linnansaari et al., 2012). These methods also have limitations and drawbacks: they cannot be applied to certain ecosystem components, have limited links with some flow regime characteristics, and require time- and money-consuming field surveys. Nevertheless, the habitat simulation technique is a good choice as it enables the assessment of the condition of fish habitats and predicts their distribution in different scenarios. One of the advanced tools for this is Mesohabitat Simulation System (MesoHABSIM) method (Parasiewicz, 2001; Parasiewicz, 2007). This approach is considered more accurate than hydrological ones since MesoHABSIM combines flow and morphology-dependent ecological data, such as the occurrence of wetted areas and the connectivity between them, local hydrodynamic conditions of depth and flow velocity, sediment distribution and composition, and the presence of shelters and refuges for the fauna. This tool has been used in a number of studies to identify river biophysical conditions, habitat deficits, and potential improvement measures (Parasiewicz, 2008; Suska and Parasiewicz, 2020), to assess bullhead fish habitat preferences (Vezza et al., 2014), to predict the distribution of bullhead fish in various habitats (Adamczyk et al., 2019) or to describe habitat distribution and e-flow requirements to support local populations (Vezza et al., 2016; Koutrakis et al., 2019).

The hydromorphological survey, which is needed for application of the MesoHABSIM approach, is one of the key steps that provides input data for a comprehensive assessment of the impact of HPP on rivers' natural flow, morphological changes and fish habitats. Thus, the precision hydromorphological assessment requires field surveys (Rinaldi et al., 2013). Remote sensing and GIS (Geographic Information Systems) tools have additionally been introduced to overcome the limitations of field observations and extend the assessment to larger spatial scales (Rinaldi et al., 2017; Bechter et al., 2018; Knehtl et al., 2018). However, it should be noted that small-scale habitat characteristics were generally better described in the field, whereas many large-scale features were better represented by remote sensing data (Knehtl et al., 2018). In the last few years, using Unmanned Aerial Vehicles (UAVs) to monitor environmental parameters became an alternative to classical remote sensing monitoring techniques. UAVs, equipped with digital cameras and lidar or combined systems (Sankey et al., 2017), are optimal for data collection in landscape research at resolutions from 0.5 to 2 cm (Clapuyt et al., 2016; Rusnák et al., 2018). Additionally, this method could be used to assess hydromorphological changes in meandering rivers (Ozcan and Akay, 2018), to collect data in different types of water bodies (Tymków et al., 2019), or obtain excellent data quality, including data for the identification of river bed substrate (Langhammer et al., 2017). The high-resolution outputs of aerial imagery provide an opportunity to go beyond riverine habitat classification and work with spatially explicit data for the detection of target components (Woodget and Austrums, 2017). The applicability of aerial photogrammetry for monitoring habitat restoration efforts was evaluated using manned aircraft and unmanned aerial vehicles (Khan et al., 2021). Aerial photographs were used as an ideal basis for mapping small ecosystems and fine-scale landscape features, such as riparian areas (Bakrač et al., 2021; Fensham and Fairfax, 2002).

The assessment of hydrological fluctuations is quite widely described in scientific literature. The analysis of hydrological changes revealed the importance of Indicators of Hydrologic Alteration (IHA) in describing the effects of river regulation (Gao et al., 2009; Zhou et al., 2020). In this way, it is possible to assess the opportunity of improving the IHA and hydrological status of regulated water systems (Pardo-Loaiza et al., 2021). The lack of continuous measurements limits hydrological analysis, as many partially or completely ungauged rivers exist (Guo et al., 2021). Fortunately, there is a relation between the water level and the corresponding discharge in the target river profile (Manfreda et al., 2020). This relation is expressed as a water level-discharge rating curve or H-Q curve. The flexibility of this curve consists of incoherent water discharge measurements focusing on boundary conditions to get a wider amplitude of records and a more precise relation (Ramírez et al., 2018). The water level is a more flexible variable in continuous recording at regular short time intervals, even hourly or minutely, and it could be done relatively easily and cost-effectively (Kabi et al., 2023). The versatility of this monitoring type makes it adaptable to various research (VanDusen et al., 2016; Ramatlapeng et al., 2023) using pressure-based water level loggers (Li et al., 2023).

The effects of HPP cascades on river aquatic ecosystems remain poorly studied, as most studies focus either on individual HPP impact (Abbasi and Abbasi, 2011; Anderson et al., 2015) or river fragmentation (Sun et al., 2023; Carolli et al., 2023). In addition, only a few studies attempt to assess the impact of individual metrics of HPPs performance on aquatic organisms' community (Yang et al., 2020) or cumulative impact assessment with a special focus on cascades of consecutive impoundments (Van Treeck et al., 2022). Therefore, the current research aims to assess the impact of hydropower cascade on hydrological changes and fish metrics downstream of each HPP via HPP multimetric based on the combination of IHA. The modern methods of hydromorphological measurements, advanced habitat simulation approach, continuous hydrological observations based on in situ data as well as an application of selected indicators of hydrologic alterations were used to achieve the set goal.

2. Study area and data

The analysed Varduva River catchment is a part of the Venta River basin located in the south-eastern part of the Baltic Sea drainage basin (Fig. 1). Rising in the Samogitian Upland (at 122.5 m above sea level), the Varduva River then flows through the Northern Samogitian Plateau and descends into the low-elevation Middle Venta Plain to its confluence with the main Venta River (at 182.5 km from its mouth). The annual precipitation in the Varduva River catchment area is 750 mm. Total evaporation exceeds 300 mm/year. Therefore, the overall annual balance is positive and creates favourable conditions for retaining water throughout the year. The drainage area of the river is 586.7 km^2 and the length is 90.3 km (Gailiušis et al., 2001). The Varduva River valley is 0.5–1.7 km wide. The river floodplain is mostly one-sided, 50–120 m wide. The river channel of the upper reaches is regulated from the source to 72.9 km. The average slope gradient of the Varduva River is 0.94 m/km; therefore, it is a typical lowland river. However, some stretches of the river can reach 1.75 m/km.

The selected hydropower cascade on the Varduva River is located from the 60th to 7th kilometre from the mouth and consists of five small hydropower plants (HPPs): Kulšėnai, Renavas, Vadagiai, Ukrinai, and Juodeikiai (Table 1). Most of them were constructed between 1995 and 2004. The hydrological observations in this river were made only from 1956 to 1973.

All HPPs were constructed in the river section meeting the criteria of EU intercalibration river type R-C4 (European Commission…, 2009) and national river type of Medium-sized rithral rivers. During the last decade (2010-2020), State monitoring was carried out in two stretches of the Varduva River: below the lowermost Juodeikiai HPP and in the middle reaches below Renavas HPP. According to the data provided by Environmental Protection Agency, the water quality elements in the Varduva River met either high or good status throughout the entire period, the concentration of dissolved oxygen ranging from 8.5 to 10 mg/l, BOD_7 – 1.9-2.5 mg/l O_2, NH_4-N – 0.04-0.08 mg/l, NO_3-N – 0.53-1.83 mg/l, Ntot – 1.24-2.38 mg/l, PO_4-P – 0.017-0.064 mg/l, and Ptot – 0.036-0.058 mg/l. Thus, the whole studied river stretch covering all five HPPs is of similar morphology and belongs to the same river type and to the same ecological status class in terms of water quality.

The main data of this research was obtained through physical monitoring and field surveys in an ungauged river, where the flow was strongly regulated by anthropogenic structures. During the surveys, the water level data of the 15-minute time step at the inflow to hydropower cascade and below each of 5 HPPs was collected. Discharge measurements for water level-discharge rating curves were carried out for each point of water level measurements. For the ecological modelling with the MesoHABSIM model, the data of polygons of geomorphic units were collected. The data on the physical characteristics of fish habitats (substrate and shelters) were indicated, and hydraulic features (river depth and flow velocity) were measured for each geomorphic unit. The fish data were also sampled during the field works. Historical observations of the Varduva River discharge were taken from the hydrological yearbooks of the Lithuanian Hydrometeorological Service for the period of 1956–1973. These data were used to obtain target discharges of the summer low-flow period.

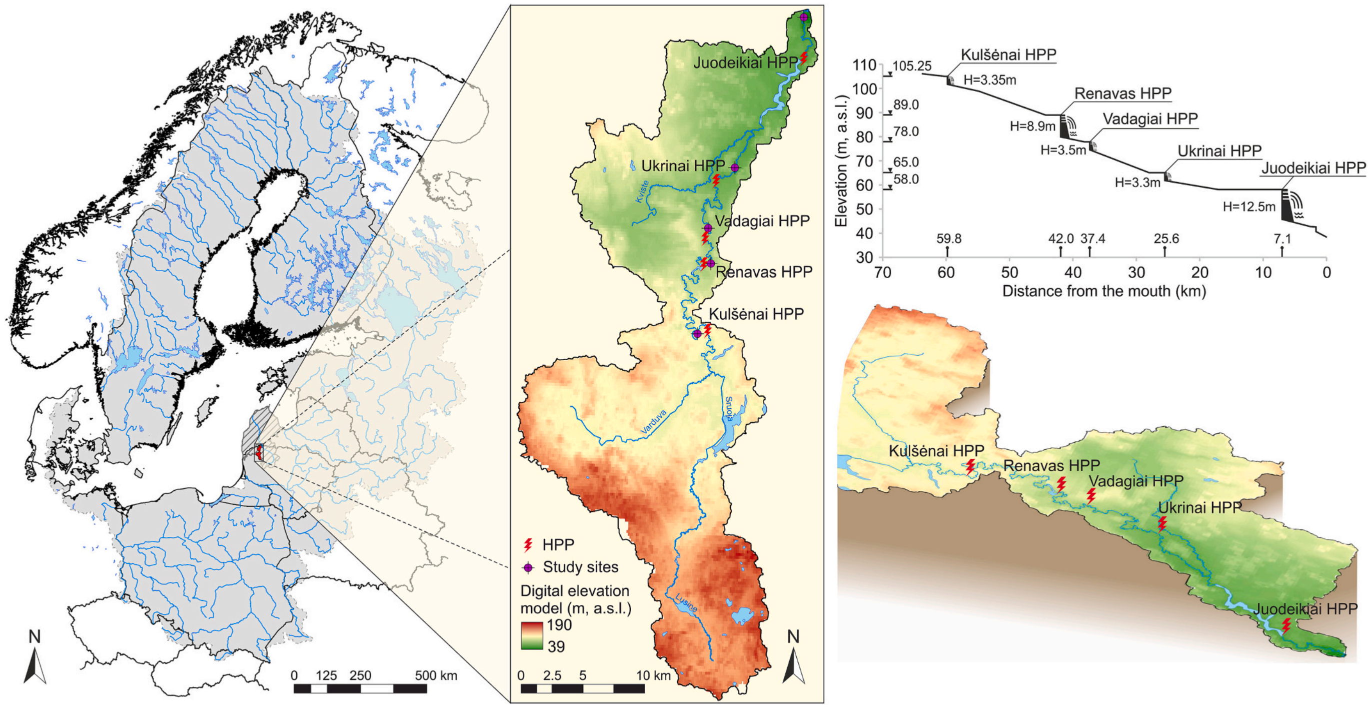

Fig. 1. Study area and longitudinal profile of selected case study river from 65th kilometre from the mouth.

Table 1
Physical characteristics of studied HPPs based on the official Reservoir exploitation and maintenance rules.

No.	HPP	Distance from the mouth (km)	Catchment area (km^2)	Year of dam/HPP construction	Reservoir area (ha)	Annual average discharge at HPP (m^3 s^{-1})
1.	Kulšėnai	59.8	333.6	1998/1998	2.2	3.60
2.	Renavas	41.4	358.6	1955/1995	29.1	3.54
3.	Vadagiai	34.6	369.7	2004/2004	5.6	3.70
4.	Ukrinai	23.8	382.5	2002/2002	9.6	3.80
5.	Juodeikiai	7.1	578.5	1979/1996	261.4	6.15

3. Methodology

The study consisted of 5 main blocks: technical properties of HPPs that determine artificial alterations, hydrological measurements, aerial mapping and ground truth data collection, fish sampling, and processing of collected data on the technical properties of hydropower cascade. The processing was carried out in two stages; the first consisted of a statistical analysis to interrelate the hydrological and ecological indicators with the operation regime of the hydropower cascade. The second stage involved habitat availability modelling based on the collected data and the conditional habitat suitability criteria for fish, using the MesoHABSIM modelling approach. This stage verified the obtained statistical relations with the more complex modelling results where spatial and temporal changes were considered. The principal scheme of the study describing the relationships between different elements in the analysis of the effects of the hydropower cascade on fish is presented in Fig. 2.

3.1. Water level-discharge rating curves

Five Solinst™ water level loggers (WLL) were installed below each selected HPP and one WLL at the inflow to hydropower cascade. The WLLs were set to record the readings every 15 min to indicate all potential hydropeaking events downstream of the HPPs. In addition, two Solinst™ atmospheric pressure loggers were used for the compensation of the fluctuations of atmospheric pressure in the water level data series. The water level observations were done during the 2021 calendar year. Additionally, the discharge measurements were carried out at each WLL. The profiles for discharge measurements were selected considering several physical factors, i.e., straight stretch without boulders, aquatic vegetation, and natural and artificial obstacles. The flow velocity measurements were carried out using Valeport 801 Electromagnetic Flowmeters at 1 m intervals in selected cross-sections and at depth ratios of 0.2, 0.6, and 0.8. Based on the collected data, the water level-discharge (H-Q) rating curves were created to recalculate water levels into the 15-minute time step discharge data series. The daily discharge was then calculated for the mesohabitat modelling.

3.2. Flow regime alterations

To comprehensively assess the operation pattern of cascaded HPPs, their potential and mutual influences, indicators of hydrologic alterations (IHA) were used to describe runoff variability (Richter et al., 1996). The indicators were divided into four main groups: magnitude, timing duration, frequency, and rate. The ecological role and significance of each IHA group were systematized and described originally by Richter et al. (1996) and adopted by Ely et al. (2020) and Maskey et al. (2022). A total of 14 different indicators of hydrologic alterations were selected as the best parameters indicating the altered flow on a fine time scale. The magnitude group of indicators consisted of average discharge (m^3 s^{-1}) of low and high pulses. The average and total duration (hours) of low and high pulses were selected as timing duration indicators. The frequency group involved a count of total cases (number) of low and

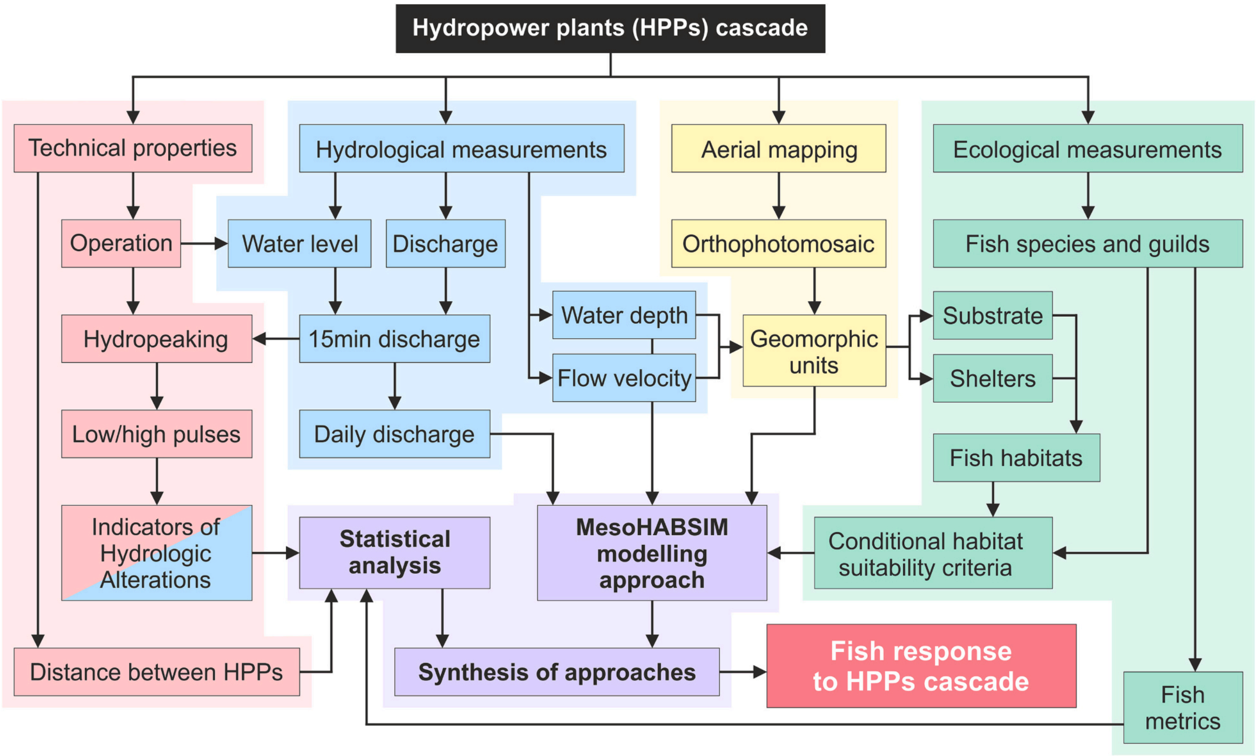

Fig. 2. The workflow of the research.

high pulses. In addition, the indicators of conditions in relative change between low and high pulses were used. They described the duration (h), amplitude ($m^3\ s^{-1}$), and rate ($m^3\ s^{-1}$ per 15 min) in pulse fall and rise conditions. All these indicators gave the overall picture of hydropower cascade potential effect and interaction between HPPs. The fine temporal scale (15-minute intervals) enabled accurate evaluation of altered flow. The Principal Component Analysis (PCA) is usually used to reduce redundant variables (McGarigal et al., 2000; Worrall et al., 2014) and single out the groups with interrelated parameters (Gajbhiye et al., 2015; Meshram and Sharma, 2018). This study used PCA to analyse the distribution regularities of flow alterations between cascaded HPPs according to the selected IHA during different bio-periods and to define the overlapping indicators.

3.3. Description and mapping of geomorphic units

The comprehensive assessment of fish habitats using the MesoHABSIM approach requires a layer of river geomorphic units (GUs) as input (Parasiewicz, 2001; Parasiewicz, 2007). The model estimates spatial and temporal changes in fish habitats due to changes in water quantity. The mapping of GUs was accomplished in several steps. First, the target low-flow discharges (multi-annual minimum, average and maximum) of the warm season (May–October) were calculated from the available historical observations. The measurements at mentioned discharges enabled to cover all possible ranges of runoff and following GUs and fluctuations of hydraulic features in the warm season. Second, a multi-rotor unmanned aerial vehicle (UAV) and digital photogrammetry were applied to create orthomosaic maps. The DJI Phantom 4 RTK UAV was used to accomplish flight missions and collect aerial imagery. The flights were conducted at 35 m above the surface, and the photos were captured with 80 % overlap. These settings allowed a pixel resolution of ~1–2 cm^2. Five ground control points (GCP) were measured with a GeoMax Zenith 40 GNSS GPS receiver to georeference orthomosaic maps accurately. The generation of orthomosaic maps was performed with Pix4Dmapper photogrammetry software. The processing of collected aerial imagery consisted of several steps: creating point clouds for each river segment, tethering of point cloud and corresponding aerial imagery to the measured GCPs, and creating orthomosaic maps based on combined aerial photography and georeferenced point cloud. The third step consisted of the delineation of GUs from generated orthomosaic maps created for four river stretches downstream HPPs. The only exception was below Juodeikiai HPP as the target section was restricted to UAV flights. Therefore, mapping in the mentioned area was carried out only by physical measurements. In the other four case studies, physical measurements were made for the reference points and GCPs. Based on the control points, different types of GU polygons were delineated from the orthomosaic maps. The GU classification described by Rinaldi et al. (2015a) and Belletti et al. (2017) was applied. The following GU types were identified based on channel morphology and hydraulic features: pool, glide, riffle, rapid, cascade, secondary channel, and backwater. The hydraulic features, such as river depth and flow velocity, were measured at a minimum of 10 points in each designated GU. The river bottom substrates and potential shelters are among the key elements that describe fish habitats. Therefore, the proportion of mesolithal (6–20 cm), microlithal (2–6 cm), akal (gravel), and psammal (sand) fractions was evaluated in each GU as well as different kinds of shelters, such as boulders, woody debris, shading, undercut bank, and different kind of aquatic vegetation (submerged, emerged and overhanging), were indicated.

3.4. Fish sampling and metrics

Fish were sampled by a wading team of 3 persons using a backpack pulse current device. One continuous electrofishing operation at low river flow was carried out in all GUs identified in the selected river reaches below the HPPs. Previous studies have shown that the species composition and rank abundance of common species do not change significantly after the first pass (Sály et al., 2009; Hanks et al., 2018). The main mesohabitat types (glide, pool, riffle and rapid) occupied most of the river channel in the studied reaches, however, in different proportions. Different fish species also preferred different depths, flow velocities, bed structures, and shelters. To reduce the differences in species proportions that might have resulted from differences in GU proportions in the study reaches, the abundance of species below the different HPPs was standardised by first calculating the abundance of individuals per 100 m^2 separately in the GUs aggregated to glide, pool, riffle and rapid mesohabitats, and then averaging them. Fish species were then assigned to habitat ecological guilds based on a classification of European freshwater fish species according to their preference for living and spawning habitat attributes and tolerance to habitat degradation (Schmidt-Kloiber and Hering, 2015). The number of species and the abundance proportions of individuals in the different guilds were calculated.

State fish monitoring has also been carried out in the river stretches below Renavas HPP (2015 and 2022), Juodeikiai HPP (2014 and 2022) and Kulšėnai HPP (2022) using the same one-run electrofishing operation (Environmental Protection Agency). Although the monitoring data were not collected at exactly the same locations, they were used to compare compliance with the data from this study.

3.5. MesoHABSIM modelling

The MesoHABSIM approach, which was used to model the impact of the HPPs on the spatial and temporal availability of suitable habitats for fish, aggregates three models: a hydromorphological model describing the spatial distribution of fish-relevant hydromorphological features; a biological model that describes the relationship between the presence and abundance of fish and river hydromorphology; a habitat model, which quantifies the area, frequency, and duration of the available habitat depending on the flow regime and local river morphology (Parasiewicz, 2001). The time series of daily data of natural (inflow) and altered (downstream HPPs) flow were applied to model the potential impact of the HPPs operation regime in 2021. To model the impact of the HPPs on the spatial and temporal availability of suitable habitats for fish, conditional habitat suitability criteria (CHSC) were used. The CHSC models have been developed and validated in previous studies for ten fish species common in the natural lowland rivers of Lithuania (Virbickas et al., 2020; Akstinas et al., 2021). Measurements of river hydraulic and fish shelter attributes on a scale of mesohabitat were conducted during the mapping of geomorphic units. Web-based Sim-Stream interface (https://mesohabsim.isprambiente.it) was used to organize the collected data and to perform mesohabitat modelling (Vezza et al., 2017; World Meteorological Organization, 2019). The availability of suitable habitat was modelled for all rheophilic fish species recorded in the Varduva River for which CHSCs were previously developed.

3.6. Impact assessment in the hydropower cascade

The effects of HPP operation on fish were assessed according to HPP performance indicators - the magnitude, timing, frequency, and rate of changes in flow during the year and in different bio-periods. Bio-periods were defined as flow conditions at different life stages of fish (Parasiewicz et al., 2018): the overwintering period (16 December–15 March), the spring spawning period (16 March–15 June), the development and growth period (16 June–15 October) and the autumn spawning period (16 October–15 December). As HPPs differed in terms of varying HPP performance indicators, a multimetric indicator for each HPP (HPP multimetric) was also constructed, combining the values of indicators reflecting different aspects of HPP performance into a single numerical expression. To construct a multimetric, the measured values of the HPP performance metrics were converted into relative values ranging from 0 (relatively strongest impact) to 1 (relatively weakest impact). For indicators whose increasing values were considered to have a decreasing negative impact on the ecosystem, the relative value in the corresponding bio-period was calculated by dividing the measured value by the highest value measured among all HPPs. The relative value of indicators for which the negative impact on the ecosystem increased with the increasing values was calculated by subtracting the ratio of the measured value to the highest value from 1. The HPP multimetric was then calculated as the average of the relative values of the HPP impact indicators. In determining the direction of ecological impacts with increasing values of each HPP performance indicator, it was taken into account that the negative ecological effect of HPP is greater the higher the rate, frequency and amplitude of the HPP induced flow alteration (Clarke et al., 2008; Korman and Campana, 2009; Meile et al., 2011; Person, 2013) and the longer the duration of the altered flow conditions (Niemi et al., 1990; Lake, 2000; Parasiewicz, 2004).

To assess the dependence of fish metrics on the length of the river section available for the life and migration of fish species between the HPP dams, the length of the stretches downstream from the dam to the beginning of the impoundment area of next dam was calculated. Below the last HPP dam in the hydropower cascade, there were no other barriers to fish migration, and the length of the section open for fish to the sea was ~190 km. To avoid the effect of the high inequality in length on the analysis results, the length of the river stretch below the last HPP was extrapolated by multiplying the maximum distance between the upper dams by the average of the ratio of the distances between the dams (larger distance divided by next smaller distance).

The impact of HPPs on habitat availability for each fish species estimated using MesoHABSIM was assessed by comparing the modelled available habitat area at reference conditions (baseline reference conditions) and under HPPs functioning. The deviation of the index of spatial habitat availability (ISH) was calculated as the ratio between the available habitat area at baseline and the altered conditions. Deviation of temporal availability of suitable habitats was quantified based on the relative increase in the cumulative continuous duration of days when the habitat area falls below the minimum threshold values, normalized between 0 and 1 by using the index of temporal habitat availability (ITH). The ISH and ITH values for the whole community were set as the minimum values among all the modelled species. The concept and calculation of ISH and ITH were described in more detail by Rinaldi et al. (2015b) and World Meteorological Organization (2019). The habitat integrity index (IH) was calculated, which is the minimum value between the ISH and ITH (Vassoney et al., 2019). To assess the impact of all HPPs on the availability of suitable habitats for fish in a uniform manner, diadromous fish species were not included in the calculation of the IH for the whole community. These species were restricted to the river section below the lowermost Juodeikiai HPP and could not access the upper reaches of the river due to the migration barrier and absence of a fish ladder. Therefore, diadromous species could not be used for a comparative assessment of the impact of HPPs on the fish communities by linking the IH to actually measured HPP performance indicators and fish metrics in all the study sites.

To assess interrelationships, the correlations were calculated between the fish metrics (proportions of abundance of different fish species, numbers of species of different ecological guilds, and proportions of abundance of individuals of different ecological guilds) and (1) the values of the single HPP performance metrics for the different bio-periods and for the whole year, (2) the values of HPP multimetric for the different bio-periods and for the whole year, (3) the length of the river stretches between the dams, and (4) the simulated IH values. Given the small sample size, Spearman and Pearson correlations were calculated, and only indicators with $R \geq 0.9$ for both types of correlation were initially selected. This helped to sort out random correlations and select only those fish indicators that correlated with potential explanatory variables in terms of both linearity and monotonicity of the relationship. Regressions were then calculated for the selected fish metrics and the independent variables, and the residual plots were analysed, leaving only those fish metrics for which the residuals showed no inconsistency in variance and followed a normal distribution.

4. Results

The HPPs in the analysed hydropower cascade of the Varduva River are featured by different technical characteristics (Table 2). The most significant differences were obtained for reservoir volume, maximum height of pressure (max head), and installed capacity. Renavas HPP, the second in hydropower cascade, stood out the most due to its features. The installed capacity of this HPP was three times higher than the neighbouring HPPs, especially those located downstream. The lowermost located Juodeikiai HPP was distinguished by the size of technical structures, however, this HPP did not affect the upstream ones. The possible amplitude of releasing discharge determined the operation regime and the maintenance of the legally defined environmental flow. As for the selected HPPs, only Ukrinai and partially Kulšėnai HPPs are able to release environmental flow via turbines. Meanwhile, other HPPs are far from the mentioned possibility, since the minimum discharge of the turbine of the second HPP (Renavas) is 8 times, the third HPP (Vadagiai) is 3 times, and the fifth HPP (Juodeikiai) is 3.8 times higher than the environmental flow (according to the Reservoir exploitation and maintenance rules). The successive HPPs destroy the integrity of the river and create some kind of isolated fragmentation of the riverine environment below HPP up to the next impoundment. These stretches below each HPP on the Varduva River differed by length. The longest isolated stretch of 15.3 km was below Kulšėnai HPP (the first HPP in the cascade), and the shortest – below Renavas HPP (the second HPP in the cascade) was only 2.9 km. Downstream located Vadagiai and Ukrinai HPPs were distinguished by relatively moderately isolated stretches of 9.4 and 5.5 km, respectively. Juodeikiai HPP (the last in the hydropower cascade) did not have any downstream barrier; therefore, the free access stretch was ~190 km consisting of a native Varduva River stretch and a stretch of the main river of Venta.

4.1. Water level-discharge rating curves

Based on the observations of water level fluctuations (Fig. 3), the records of inflow WLL showed a natural hydrological regime with frequent peaks due to rainfall events and sudden thaws, typical of the rivers from Western Lithuania. The water levels ranged between 80 and 150 cm till the middle of May 2021. During the rest of the year, the water level and its amplitude slightly decreased, while the minimum values were recorded at the end of July and the beginning of August. However, the water level did not fall below 68 cm above the head of WLL. The water level reached flash peaks during the autumn season, which indicated a decisive factor of rainfall influence on the hydrological regime of the Varduva River. The records of WLLs installed below Kulšėnai HPP (the first in the hydropower cascade) indicated the first alterations of the natural regime. The hydropeaking was recorded for almost half a year (till the middle of June). On average the water level fluctuated in the range of 30 cm. It seems that only in the second part of June, the HPP stopped working, and the water level became close to natural. At the beginning of October, the hydropeaking mode was renewed since the water level fluctuations became sharper compared with the natural inflow. Below Renavas HPP, the water level records revealed another operation model when HPP had a relatively high-capacity reservoir in the middle of the hydropower cascade. During the wet period, Renavas HPP used its reservoir volume daily to accumulate and redistribute runoff. The WLL observations indicated large water level fluctuations and sudden changes below the HPP. A clearly expressed hydropeaking was determined only from the middle of June 2021. At the same time, Kulšėnai HPP stopped its operation; however, Renavas HPP continued to work in the hydropeaking regime due to its reservoir capacity. During the summer low-flow period, the water level ranged around 20 cm

Table 2
Technical characteristics of HPPs based on the Reservoir exploitation and maintenance rules. An asterisk indicates free access stretch of the Varduva River/and the main Venta River below the confluence with Varduva River.

No.	HPP	Reservoir volume (thous. m^3)	Max head (m)	Installed capacity (kW)	Type/quantity of turbine	Turbine amplitude, (m^3 s^{-1}, max/min)	Legally defined environmental flow (m^3 s^{-1})	Distance downstream of HPP to next impoundment (km)
1.	Kulšėnai	22.4	3.35	115	K/1	6.0/0.5	0.20	15.3
2.	Renavas	704	8.90	300	K/1	9.0/2.4	0.39	2.9
3.	Vadagiai	56.0	3.50	110	K/1	5.7/1.2	0.41	9.4
4.	Ukrinai	80.0	3.30	110	K/1	6.0/0.5	0.46	5.5
5.	Juodeikiai	10520	12.5	1018	K/2	8.0/3.5	0.91	7.1/182.5*

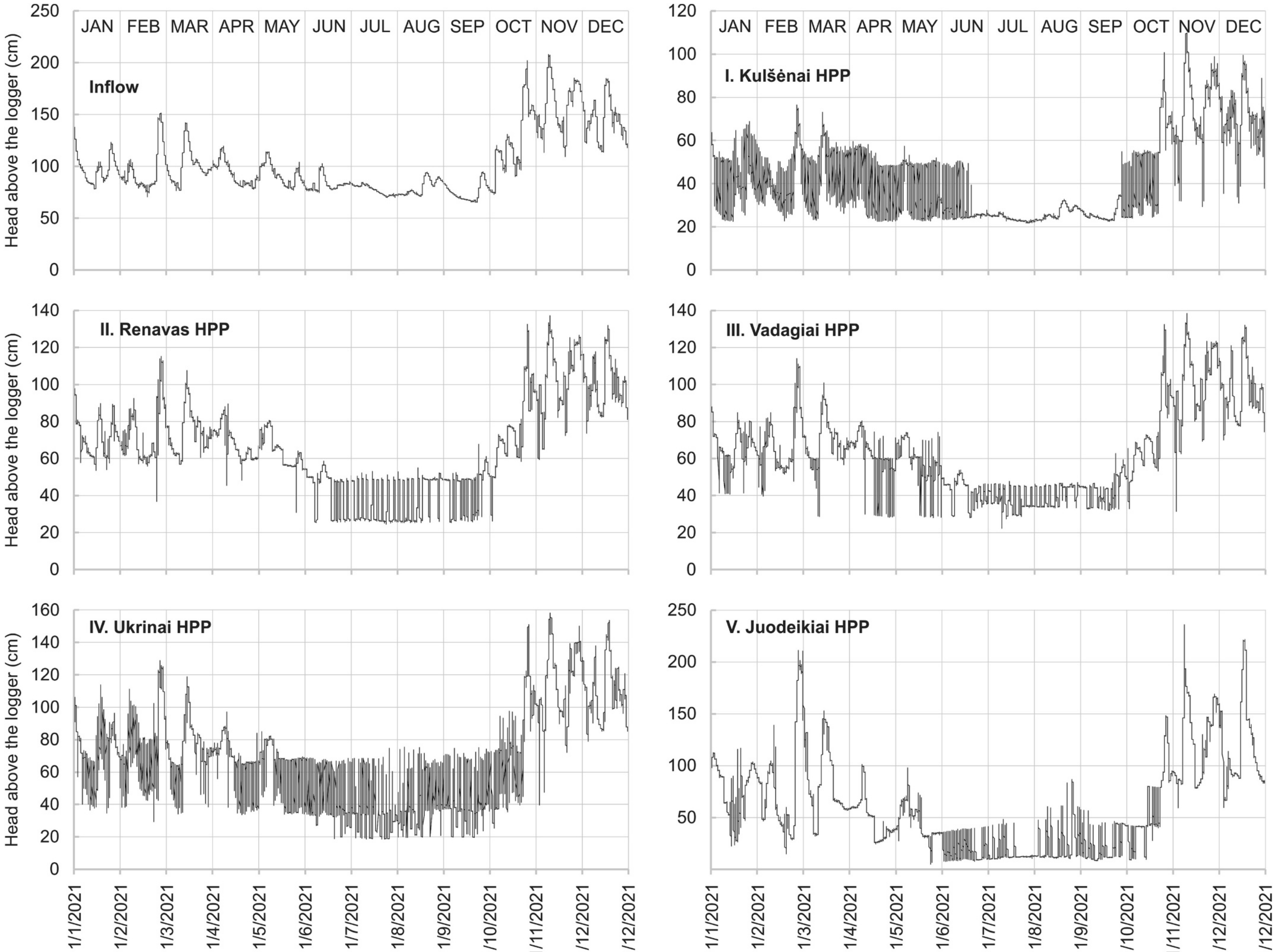

Fig. 3. Water level fluctuations at the inflow to hydropower cascade and downstream of each HPP of the Varduva River.

amplitude under the influence of Renavas HPP. Below Vadagiai HPP, the water level fluctuations were closely related to Renavas HPP operation since the reservoir of Vadagiai is ten times less in volume than the reservoir of Renavas. The records of WLL below Vadagiai HPP indicated similar patterns of water level fluctuations as below the Renavas HPP. In addition, by the end of May, the sharp alterations of Vadagiai HPP were indicated, afterwards this HPP did not operate and all water level fluctuations with some lag (due to the compensating influence of Vadagiai HPP reservoir) were caused by Renavas HPP. Juodeikiai HPP was the last technical structure studied in the hydropower cascade. This HPP with the largest volume reservoir (up to 15 times larger than Renavas HPP reservoir) can accumulate and distribute a large amount of water on demand. Based on the measurements of WLL below Juodeikiai HPP, water level fluctuations became relatively natural until May 2021. However, the situation changed at the beginning of June when HPP began to operate in clearly expressed hydropeaking mode. The obtained amplitude was around 25 cm in the first part of the summer months. One prolonged period of very low water levels (only 12 cm above the WLL head) was observed in the last decade of July. Since August, the amplitude of the hydropeaking increased up to 40–50 cm.

The discharge measurements were carried out in cross-section profiles at each WLL. For the last 50 years, the discharge has not been measured in the Varduva River. Only the data for the period of 1956–1973 was available. After such a long break, the discharge was measured 10–13 times in each of the 6 profiles (Appendix A, Table A.1). The obtained values ranged widely depending on the profile. At the inflow profile, the measured discharges varied between 0.32 and 10.37 m^3 s^{-1}. The profile below Kulšėnai HPP indicated similar values (0.36–10.66 m^3 s^{-1}) since this HPP did not operate during the summer low-flow period. The highest amplitudes were found below the remaining HPPs, which led to a dramatic decrease in discharge at the lower boundary of their hydropeaking. For example, below Renavas and Vadagiai HPPs, the lowest discharge was 0.16 m^3 s^{-1}. Meanwhile, the legally defined environmental flow for these HPPs is 0.39 and 0.41 m^3 s^{-1}, respectively. Similar runoff conditions were determined below Ukrinai HPP where the lowest measured value was only 0.15 m^3 s^{-1} (environmental flow – 0.46 m^3 s^{-1}), and the largest discharge was 14.28 m^3 s^{-1}. Juodeikiai HPP also operated with a wide hydropeaking range. Several times, the measured discharge was <0.40 m^3 s^{-1}, although the legally defined environmental flow for this HPP is 0.91 m^3 s^{-1}. These numbers indicated non-compliance with the legal requirements in the absence of any control measures. The discharge measurements together with the data of water levels highlighted the crucial impact of HPPs operation on the hydrological regime.

The measured discharges were matched with the corresponding water levels at the exact time of measurements. Six water level-discharge rating (H-Q) curves represented by profiles of interest were created for the Varduva hydropower cascade (Fig. 4). Most profiles had regular H-Q curves which could be described as a logarithmic growth. However, some profiles had almost linear relations such as Kulšėnai and Juodeikiai. Despite these differences, the relations had no statistical outliers and most measurements were close to the rating curves. Accordingly, the water level-discharge rating curves were ready to be applied for discharge recalculation on the 15-minute time step for the analysis of artificially induced hydrological alterations.

4.2. Regulated runoff alterations

The comparison of flow rates between inflow and downstream of each HPP showed clearly expressed hydropeaking with a certain mode of operation. The main characteristics of low and high pulses were estimated using the data of recalculated discharge at 15-minute time step (Table 3). Fourteen indicators of hydrologic alterations were chosen to describe the regulated flow. From the annual perspective, each indicator varied differently along the hydropower cascade. The analysed indicators at selected HPPs differed greatly from the natural inflow. All HPPs had a shorter average duration and a longer total duration of low pulses. Meanwhile, the shortest average duration of low pulses between HPPs was found for Kulšėnai and Ukrinai HPPs, which have turbines with a wide discharge range. The same was estimated for the number of low pulse cases downstream of HPPs because the HPPs with the mentioned turbines produced more fluctuations than the others. Similar patterns were obtained for the high pulse indicators. The main difference in the total duration of analysed variables at the Ukrinai and Juodeikiai HPPs was detected. The total duration of low pulses was greater than the total duration of high pulses. For example, below Ukrinai HPP, the total duration of low pulses was 3017 h per year, while the total duration of high pulses was 1877 h. More pronounced differences were recorded below Juodeikiai HPP, where the total duration of low pulses was almost 1500 h longer than the high pulse duration. The natural inflow characteristics of pulse fall and rise indicators highlighted the magnitude of altered flow, especially for the average duration of pulse fall and rise. The naturally induced pulse fall and rise lasted 36.9 and 29.3 h, respectively. These indicators varied between 1.1 and 3.5 h under the influence of HPPs operation. Similar tendencies were estimated for pulse average fall and rise rates: the natural decrease and increase in pulses were 0.022 and 0.038 m^3 s^{-1} per 15 min. Those indicators increased between 0.160 and 0.793 m^3 s^{-1} per 15 min for the HPP regulated flow. The highest runoff regulation was found for the HPPs that had reservoirs with the smallest volume. Kulšėnai and Ukrinai HPPs were typical examples of run-off-river hydropower plants with small capacity reservoirs and wide amplitude turbines. Accordingly, they had the highest amount of low and high pulse cases, the shortest pulse fall and rise time, and the highest fall and rise rates. Due to the exploitation of the largest volume reservoirs, Renavas and Juodeikiai HPPs mitigated the upstream-generated alterations. The advantage of their larger capacity enabled more even but longer redistribution of runoff. In addition, the mentioned HPPs could not operate in the transit regime due to the relatively small natural inflow compared to the high lower boundary of discharge of their turbines. Therefore, the prolonged accumulation and the release were unavoidable in order to operate during the summer low flow period. Thus, the average duration of low and high pulses downstream of Renavas and Juodeikiai HPPs was relatively longer than the others.

The indicators of altered flow were calculated for four main fish bioperiods (Appendix A, Table A.2). Fig. 5 presents alterations of the

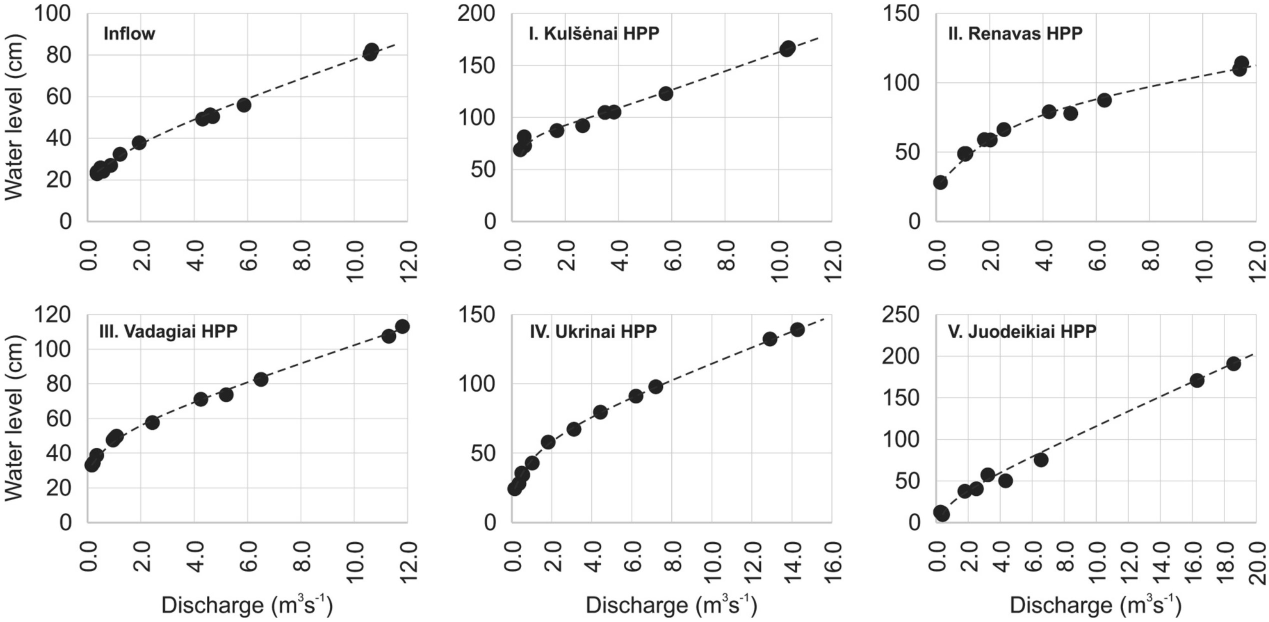

Fig. 4. Water level-discharge rating curves at the inflow to hydropower cascade and downstream of each of HPP of the Varduva River.

Table 3
Indicators of hydrologic alterations for 2021.

Indicators of hydrologic alterations	Natural inflow	Kulšėnai HPP	Renavas HPP	Vadagiai HPP	Ukrinai HPP	Juodeikiai HPP
Low pulse ave duration (h)	44.3	1.6	15.6	12.2	3.2	17.5
Low pulse total duration (h)	711	1540	1436	1406	3017	2301
Low pulse total cases	17	1466	62	126	1212	86
Low pulse ave discharge ($m^3\ s^{-1}$)	2.13	2.16	2.58	1.6	1.43	1.42
High pulse ave duration (h)	24	1.7	21.4	10.5	2.1	8.8
High pulse total duration (h)	581	1743	1396	1180	1877	809
High pulse total cases	26	1489	47	112	1189	85
High pulse ave discharge ($m^3\ s^{-1}$)	7.04	4.84	4.48	4.01	3.57	4.75
Pulse fall ave duration (h)	36.9	1.5	2.6	1.9	1.3	3.5
Pulse fall ave amplitude ($m^3\ s^{-1}$)	1.64	3.43	1.72	1.84	2.46	2.21
Pulse fall ave rate ($m^3\ s^{-1}$/15 min)	0.022	0.755	0.222	0.479	0.528	0.16
Pulse rise ave duration (h)	29.3	1.1	2.7	2.3	1.1	2.9
Pulse rise ave amplitude ($m^3\ s^{-1}$)	2.86	2.96	1.63	1.75	2.46	2.51
Pulse rise ave rate ($m^3\ s^{-1}$/15 min)	0.038	0.793	0.216	0.445	0.629	0.218

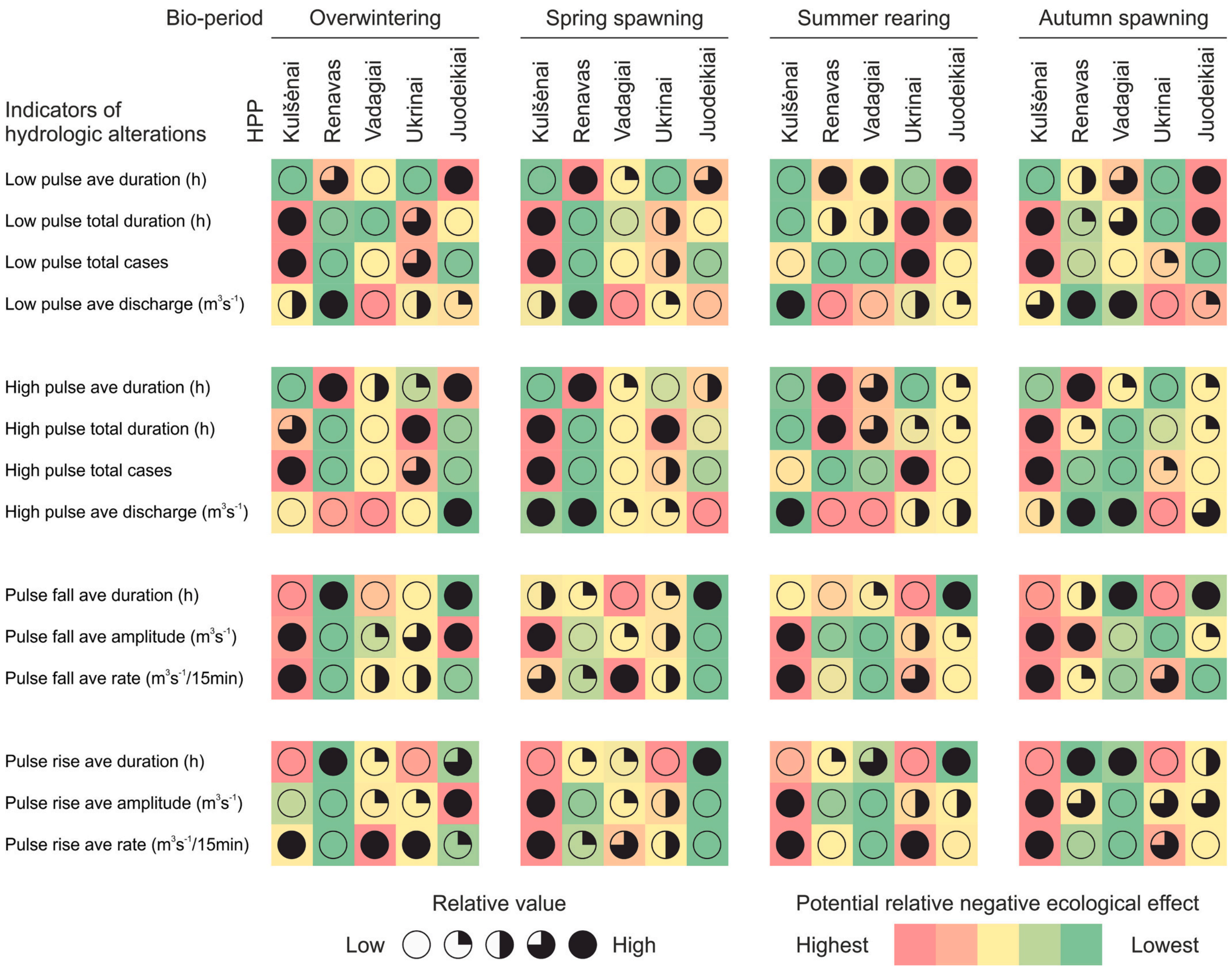

Fig. 5. Distribution of relative indicators of hydrologic alterations along HPPs (filled circle – the highest value, transparent circle – the lowest value) and their potential relative negative ecological effect (red – highest, green – lowest) during four bio-periods.

mentioned indicators along the hydropower cascade and their potential relative ecological effect. In the overwintering and spring spawning bio-periods, Kulšėnai and Ukrinai HPPs distinguished by the longest total duration of low and high pulses and the highest amount of pulse cases. Due to the already mentioned peculiarities of the reservoir capacity, the influence of the mentioned HPPs did not affect the downstream HPPs. Therefore, Renavas and Juodeikiai HPPs had their own specific operation regime, consisting of the longest average duration the shortest total duration and the least total cases of pulses per the overwintering and spring spawning bio-periods. No clear patterns of the pulse fall and rise indicators were found. In the summer rearing and growth bio-period, the lowest impact was produced by Kulšėnai HPP (the first in the hydropower cascade) where the smallest amount of pulse cases and their shortest duration was established. Renavas HPP strongly regulated the average duration of the pulses and caused the smallest average discharge of low pulse. The downstream Vadagiai HPP was dependent on the operation regime of Renavas HPP. Therefore, most of the indicators of hydrologic alterations had a similar character. During the summer rearing and growth bio-period, Ukrinai HPP was distinguished by a high number of pulsations and relatively high values of pulse fall and rise indicators. Juodeikiai HPP (the last in the cascade structure) produced relatively moderate hydrological alterations, except for the low pulse duration indicators, which were among the highest and resulted in prolonged time periods of the low pulse conditions.

The analysed indicators of hydrologic alterations were combined in PCA analysis to establish the main similarities and differences of 5 HPPs according to the patterns of altered flow by the bio-periods (Fig. 6). Two components described even 71.6 % of all variations. The first component combined the average duration of the low and high pulses, as well as the pulse average fall and rise amplitude and rate. Meanwhile, the second component consisted of the total duration and the average discharge of low and high pulses. The remaining indicators, such as total cases of low and high pulses and average duration of pulse fall and rise, varied between the components, showing no clear relation. According to these components, the distribution of analysed HPPs revealed several clusters of the bio-periods. In the overwintering bio-period, Kulšėnai, Ukrinai, and Vadagiai HPPs were strongly related to the first component. The second component was dominant for Juodeikiai HPP in the wintertime, while Renavas HPP was distinguished by the strong effect of the longest duration of pulse rise and fall, and the least number of low and high pulses cases. Also, the second component separated the winter period from spring by relatively higher values. The HPPs mostly distributed

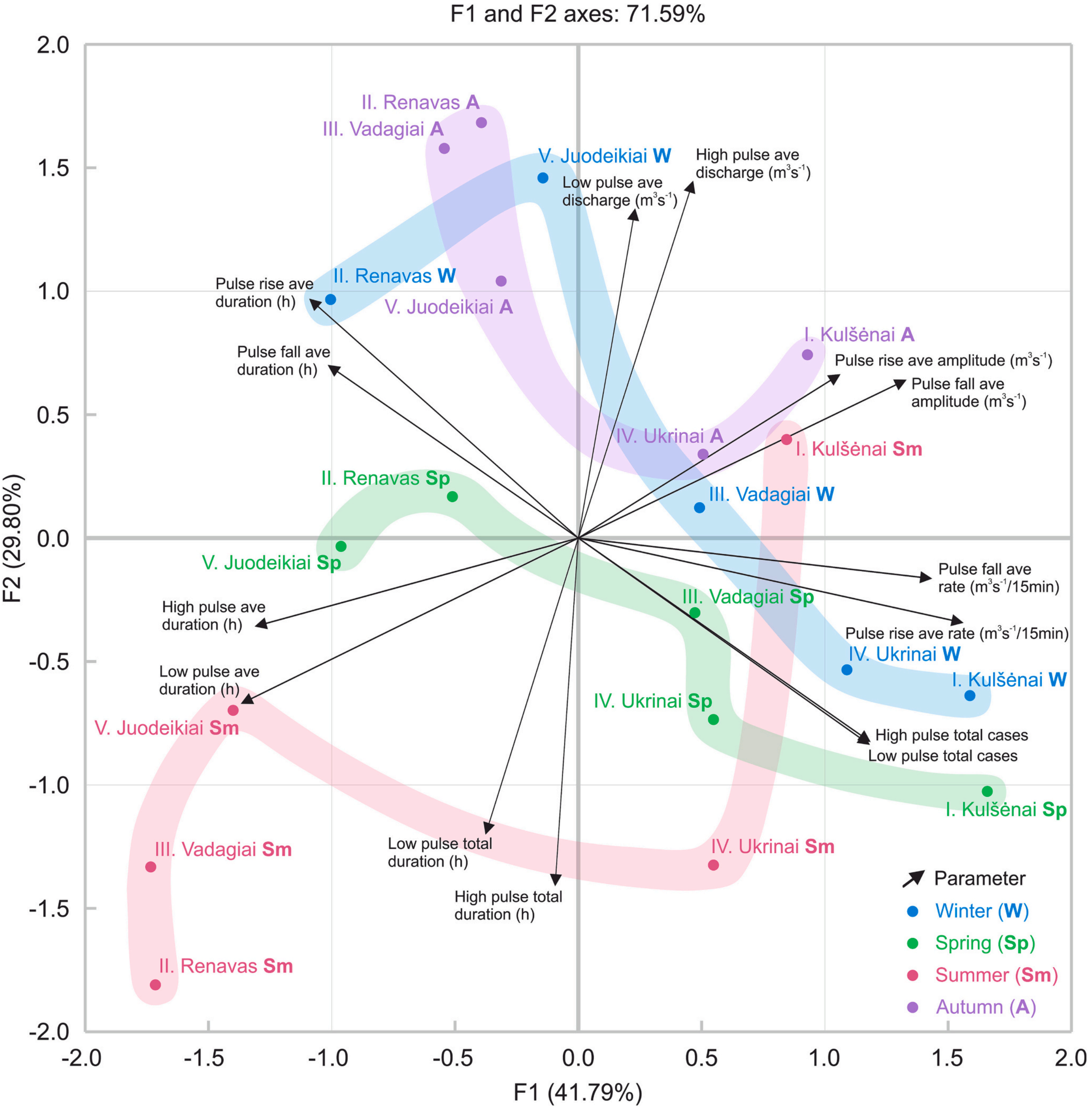

Fig. 6. Distribution of HPPs in different bio-periods by indicators of hydrologic alterations according to PCA analysis.

closer to the first component during the springtime. Only Kulšėnai and Ukrinai HPPs were partially affected by the indicators of the second component, i.e., the relatively longest duration of the low and high pulses, and the lowest average discharge of low pulse. The summer rearing and growth bio-period showed the highest scattering of selected HPPs among the components. Renavas HPP with the downstream located Vadagiai HPP had similar behaviour of hydrological alterations. This clearly confirmed the dependence of Vadagiai HPP on the operation mode of Renavas HPP in the summer period. Their difference with respect to the second component revealed a slight mitigation of the negative effect of Renavas HPP due to the compensation effect of Vadagiai reservoir. Both HPPs were described as objects that caused the longest low pulse duration and one of the smallest low pulse average discharges. Similar tendencies were obtained for Juodeikiai HPP, which had similar turbine properties to Renavas HPP (in terms of the relative difference between the turbines amplitudes and the legally defined environmental flow). Ukrinai HPP was featured by a relatively large number of cases of low and high pulses, small low pulse discharge, and rather long duration of low and high pulses. Meanwhile, Kulšėnai HPP completely differed from the other HPPs during the summer bio-period revealing a unique operation mode, especially along the second component. In the autumn bio-period, the pattern of HPPs differed from previous periods, but their interconnections still had some similarities. In the summer period, Renavas and Vadagiai HPPs were close to each other like Ukrinai and Kulšėnai HPPs in the spring and winter bio-periods but on the opposite side of the second component.

Based on PCA analysis, the specific indicators of hydrologic alterations were chosen and recalculated to the relative values for the construction of HPP multimetric (Table 4). The high pulse cases were removed from the list of indicators due to overlap with the low pulse. Besides, the indicators of total low and high pulses duration were rejected since the average duration of low and high pulses was interrelated with the technical features (mainly permeability) of the installed turbines. The pulse fall and rise indicators have been used to describe the conditions during the change between low and high situations. Therefore, pulse fall and rise duration as well as their average amplitudes were selected. The indicators of pulse fall and rise rates were not considered due to their derived value, which was based on the ratio between amplitude and time. For each selected indicator, the relative values revealed the potential impact distribution along the hydropower cascade during the summer bio-period. Almost every indicator disclosed one or a few HPPs with a relatively large impact compared to the other HPPs. Kulšėnai HPP distinguished itself by high impact according to the average amplitude of pulse fall and rise. Meanwhile, the high impact of Renavas HPP was established even via four indicators: the average duration and average discharge of low and high pulses. Similar tendencies were found in the case of Vadagiai HPP, except for the high pulse average duration. Ukrinai HPP was responsible for high impact via three indicators (low pulse total cases, and average duration of pulse fall and rise). The lowermost Juodeikiai HPP highly affected only the low pulse average duration. To assess the combined influence of analysed indicators, the HPP multimetric was calculated as the average value of all indicators for each HPP in the hydropower cascade and used for further connection with the fish metrics.

4.3. GU mapping results

The changes in the hydrological regime affected river hydromorphological conditions by changing its hydraulic features and types of geomorphic units in relation to water quantity. During the field surveys in the Varduva River, the geomorphic units (GUs) were mapped 17 times at different discharges in a cascade of five hydropower plants. The mapping of GUs was performed at least at 3 different discharges in each target case study: 4 times below Kulšėnai HPP, 3 below Renavas HPP, 3 below Vadagiai HPP, 3 below Ukrinai HPP, and 4 times below Juodeikiai HPP. GUs survey was done at a multi-annual minimum, average, and maximum of low-flow discharge situations. According to the input data requirements of the MesoHABSIM model, the length of the river reach was at least 10 river widths. The surveyed reach lengths varied from 162 m below Vadagiai HPP to 314 m below Kulšėnai HPP. The reach length was the same for each case, regardless of the changes in discharge. The total mapped area of each site varied from 2074.0 m^2 to 3336.4 m^2 and depended on the discharge and the length of the reach. In the mapped area, the largest relative difference of 432.1 m^2 due to the changes in river discharge was obtained below Renavas HPP. In an area of 213.8 m^2 (between the lowest and highest discharges), the smallest differences were determined below Ukrinai HPP. The distribution of geomorphic units varied depending on the selected river reach and the magnitude of the discharge (Fig. 7). All defined types of GUs (pool, glide, riffle, rapid, cascade, secondary channel, and backwater) were found only below Juodeikiai HPP. The most frequent geomorphic unit was a glide. Glides occupied from 40.2 % to 68.0 % of the total mapped area in 5 selected reaches of the Varduva River. The second most frequent GU was a pool, which was identified in all discharge situations. Only in the river reach below Kulšėnai HPP, the second largest GU was riffle. Riffles occupied 27.5 % to 32.3 % of the total mapped area. The rapid GU was found in almost all field surveys, except for very low discharge situations below Renavas and Ukrinai HPPs. The area of rapids tended to increase together with an increase in discharge. Cascade, secondary channel, and backwater were the rarest geomorphic units; they were identified only several times below Juodeikiai HPP. Accordingly, the mentioned GUs comprised only 0.6 % to 5.3 % of the total mapped area and created relatively small but unique habitats. The total number of GUs per river reach varied from 12 to 26. The site below Juodeikiai HPP was the second shortest but had the highest number of GUs (21–26).

In addition to the GU mapping, the hydraulic measurements of river depth and flow velocity were carried out in each GU unit of the studied river reaches. The changes in hydraulic features with respect to the

Table 4
The relative values of indicators of hydrologic alterations (from 0 - relatively strongest impact to 1 - relatively weakest impact) used to construct the multimetric as HPP impact indicator for the summer bio-period.

Indicators of hydrologic alterations	Ecological impact when indicator increases	Relative values of indicators of hydrologic alterations				
		Kulšėnai HPP	Renavas HPP	Vadagiai HPP	Ukrinai HPP	Juodeikiai HPP
Low pulse ave duration (h)	Increase	0.92	0.10	0.16	0.76	0.00
Low pulse ave discharge (m^3 s^{-1})	Decrease	1.00	0.13	0.23	0.50	0.36
Low pulse total cases	Increase	0.80	0.93	0.93	0.00	0.89
High pulse ave duration (h)	Increase	0.95	0.00	0.35	0.98	0.72
High pulse ave discharge (m^3 s^{-1})	Increase	1.00	0.27	0.27	0.66	0.63
Pulse fall ave duration (h)	Decrease	0.58	0.54	0.64	0.49	1.00
Pulse rise ave duration (h)	Decrease	0.37	0.48	0.77	0.29	1.00
Average amplitude of pulse fall and rise (m^3 s^{-1})	Increase	0.00	0.76	0.81	0.36	0.50
HPP multimetric	Decrease	0.70	0.40	0.52	0.50	0.64

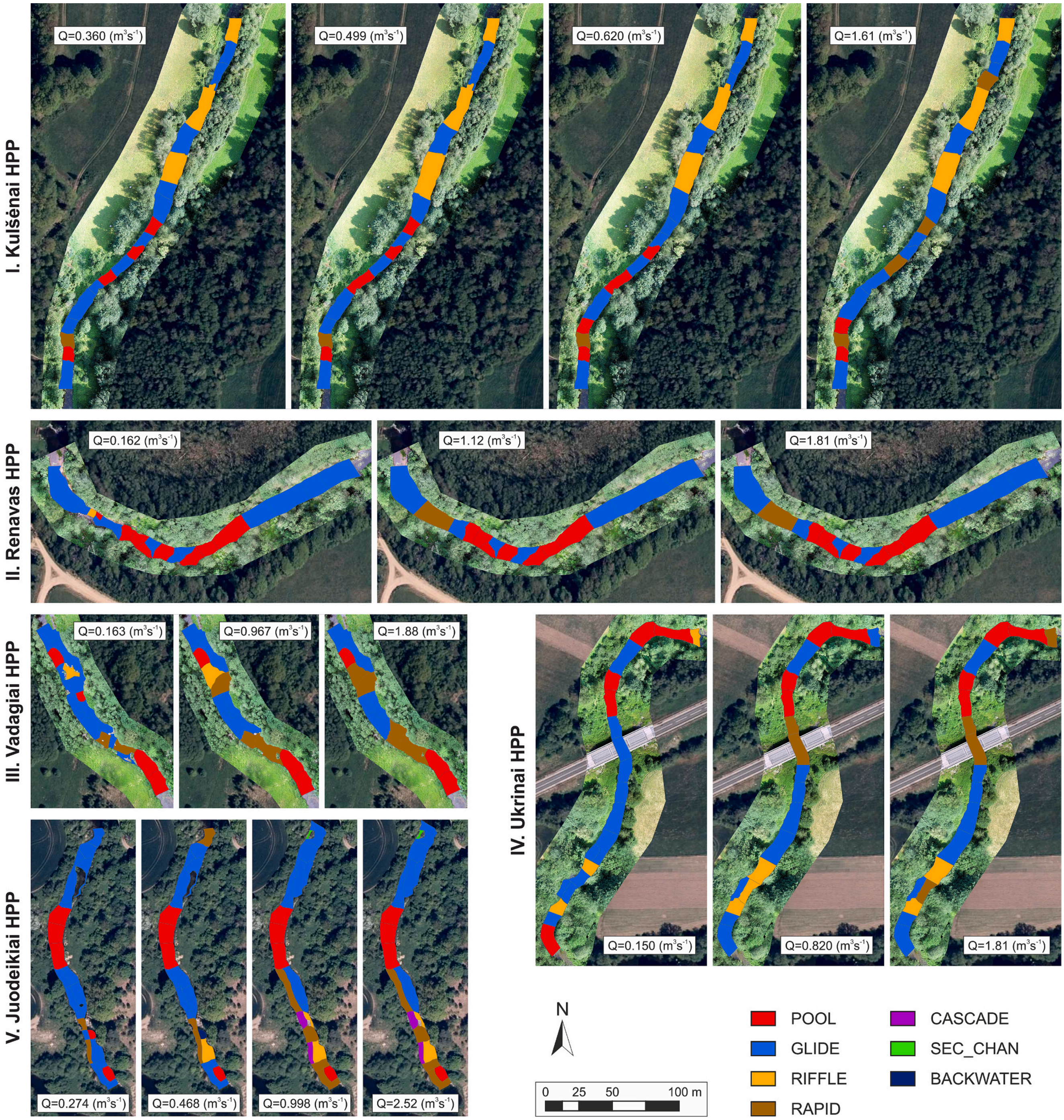

Fig. 7. Results of GU mapping at selected river reaches downstream each target HPP.

increase of discharge expand a better understanding of the effect of artificial hydrological alterations on repetitive certain hydraulic conditions. The changes in river depth and flow velocity directly affected the fish habitat environment and transformed GUs from one type to another. Fig. 8 displays one of the best examples how river depth and flow velocity distributed depending on the increase of discharge of the summer low-flow. The average values of each defined GU indicated clear differences between their types. The pool GU was, on average, 28 cm deeper but, at the same time, 0.081 m/s slower than the glide unit. Both GUs gained a consistent increase in river depth and flow velocity together with the increase in discharge. Meanwhile, the rapid GU was of almost the same depth as the glide but had significantly higher flow velocities. The obtained differences varied, on average, between 0.228 and 0.377 m/s. The riffle GU was described as a shallower polygon with relatively high velocities like in a rapid. Only below Juodeikiai HPP, the cascade GU with average flow velocities exceeding 1 m per second was identified. The channel geometry determined the relative change in river depth and flow velocity due to increasing discharge. Below Kulšėnai HPP, the flow velocity strongly increased, but depth did not change significantly. In the other studied reaches, these changes were more uniform. The exception was found below Juodeikiai HPP, where river depth was not strongly affected by the increased discharge in the GUs of faster flow (rapid and riffle), but the velocities themselves increased noticeably.

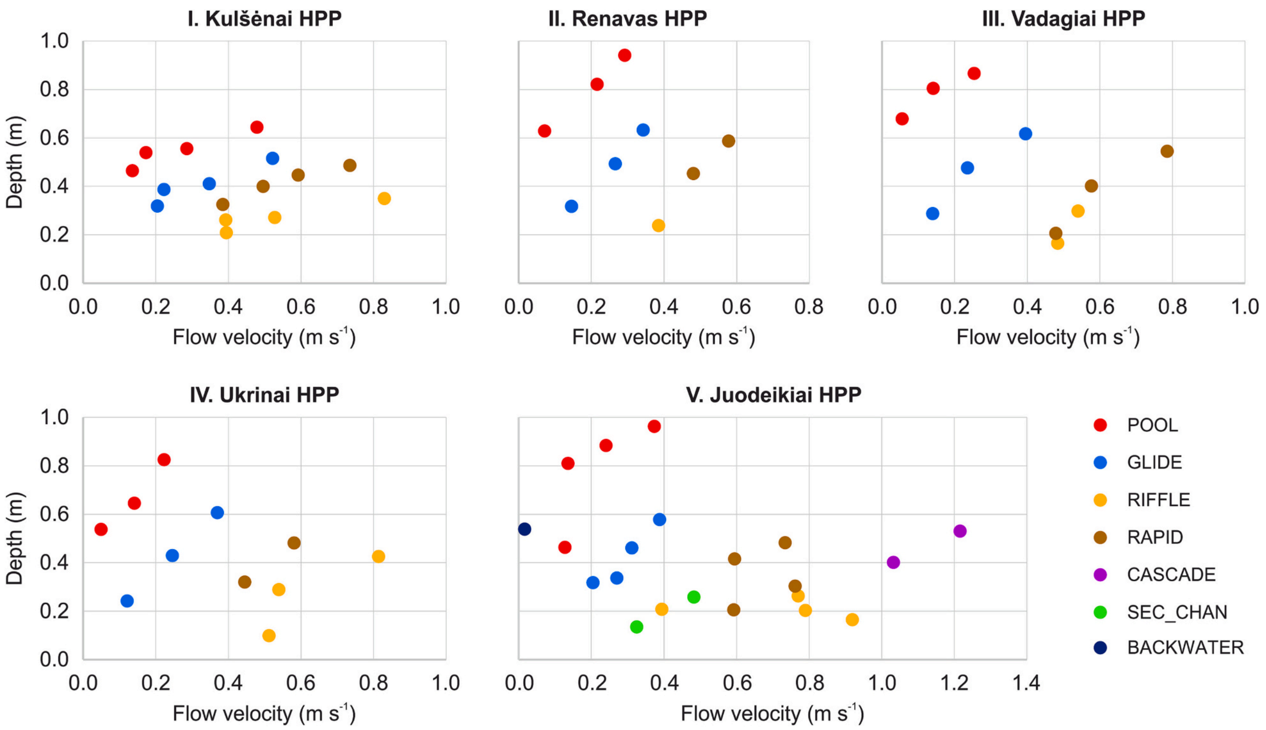

Fig. 8. Changes in hydraulic features in each GU downstream selected HPPs.

4.4. *Fish sampling*

In total, 19 fish species were recorded in the Varduva River, i.e., from 8 to 11 species in the stretches of the river within the hydropower cascade and 15 species below the lowermost Juodeikiai HPP (Appendix A, Table A.3). Four fish species were found only in this river stretch, three of which were anadromous (the Atlantic salmon *Salmo salar*, the sea trout *Salmo trutta*, and the vimba bream *Vimba vimba*). According to selected habitat attributes and tolerance to degradation, species were distributed among 19 ecological guilds (Table 5). The river stretches below the Renavas and Ukrinai HPPs stood out from the other stretches by the particularly low proportion of lithophilic fish and the lowest diversity of fish species that are intolerant to habitat degradation. The river stretches below Kulšėnai and Juodeikiai HPPs were distinguished by the lowest proportion of non-specialised eurytopic and phyto-lithophilic fish, and the highest proportion of individuals of species intolerant to habitat degradation. The river stretch below Vadagiai HPP occupied an intermediate position in terms of the proportions of the above-mentioned ecological guilds.

State monitoring data for 2014–2015 and 2022 showed that the proportion of eurytopic and phyto-lithophilic fish in the river stretches below Kulšėnai and Juodeikiai HPPs (22.6–32.7 %) was twice as low as below Renavas HPP (67.2–73.9 %). The latter stretch of the river was characterised by a lower diversity of rheophilic species and a particularly low diversity and proportion of habitat degradation intolerant fish (Appendix A, Table A.4). Even though the monitoring of fish in the river

Table 5
Number of species (NbSp) and proportion of individuals (N%) of different ecological guilds in the surveyed stretches in 2021 (Guilds: Hab – habitat, Habdeg – habitat degradation, Mig – migration, Rep – reproduction, Spwn – spawning).

Fish metric	Kulšėnai HPP		Renavas HPP		Vadagiai HPP		Ukrinai HPP		Juodeikiai HPP	
	SpNb	N %	SpNb	N %	SpNb	N %	SpNb	N %	SpNb	N %
Hab eurytopic	3	24.70	4	82.12	4	42.43	4	59.03	4	13.80
Hab limnophilic	1	0.08	1	0.01						
Hab rheophilic	6	75.22	4	17.86	7	57.57	4	40.97	11	86.20
Habdeg intermediate	1	1.60	2	2.98	2	7.51	2	2.11	3	10.96
Habdeg intolerant	4	45.66			4	33.37	1	17.34	7	46.32
Habdeg tolerant	3	50.07	4	96.89	4	59.00	4	80.26	4	35.40
Mig diadromous									3	11.87
Mig potamodromous medium							1	0.28		
Mig potamodromous short	10	100	9	100	11	100	7	99.72	12	88.13
Rep lithophilic	3	43.72	2	0.22	4	31.26	1	0.28	7	44.88
Rep litho-pelagophilic							1	0.28		
Rep ostracophilic	1	0.16			1	0.67			1	1.27
Rep phytplithophilic	2	24.54	4	82.12	2	41.64	3	58.74	2	11.76
Rep phytophilic	1	0.08	1	0.01	1	0.12			2	1.51
Rep psammophilic	2	27.14	2	17.64	2	24.30	2	23.35	2	32.92
Rep speleophilic	1	4.36			1	2.02	1	17.34	1	7.68
Spwn euryoparous	4	54.09	5	84.97	4	76.93	5	60.86	5	47.32
Spwn limnoparous	2	0.25	1	0.01	2	0.80			2	2.05
Spwn rheoparous	4	45.66	3	15.01	5	22.27	3	39.14	8	50.63

sites below the HPP was not carried out at the same locations, and the species abundance was assessed at the whole sampled stretch, rather than at the mesohabitat scale, the proportions of fish in the different ecological guilds were similar to those in the present study. During the last monitoring in 2022, fewer species were detected below Renavas and Juodeikiai hydropower plants (all of which were also recorded in this study) (Appendix A, Table A.5). However, single individuals of 3 species were found below Kulšėnai HPP in 2022 that were not recorded in 2021 (the rheophilic species spined loach *Cobitis taenia*, and eurytopic, habitat degradation tolerant species three-spined stickleback *Gasterosteus aculeatus* and perch *Perca fluviatilis*). These species were included in the overall species list when analysing the changes in the number of species belonging to different guilds within the hydropower cascade.

4.5. MesoHABSIM modelling results

According to the modelling results, the Kulšėnai HPP had the lowest impact on habitats suitable for fish. All modelled fish species had ITH values >0.9. The lowest ISH value was calculated for the intolerant fish species spirlin *Alburnoides bipunctatus*. Consequently, the IH value for the whole community was 0.86 (Table 6). The impact of Juodeikiai HPP on the spatial availability of habitats suitable for potamodromous fish was similar to Kulšėnai HPP. The operation of the HPP had a greater impact on the temporal availability of habitats suitable for chub *Squalius cephalus* and bullhead *Cottus gobio*. The ISH values for these species and the IH value for the whole community were 0.77. The effect of Juodeikiai HPP on the spatial and temporal availability of suitable habitats for anadromous species was at a similar level, with ISH and ITH values ranging from 0.73 to 0.99. No species had ITH values exceeding 0.83 in the stretch of the river below Vadagiai HPP, except the lowest estimated value of 0.73 for the dace *Leuciscus leuciscus*, the Eurasian minnow *Phoxinus phoxinus* and the spirlin. The impact of the HPP activities on the spatial availability of suitable habitat for the latter species was even higher, with an estimated ISH value of 0.65. Ukrinai HPP made an even stronger impact on the availability of suitable habitats. The ITH values of 4 out of 7 modelled species ranged between 0.61 and 0.63, the whole community IH value being 0.61. The negative impact of the operation of Renavas HPP was the largest among all hydropower plants, with an estimated ITH value of only 0.51 for spirlin, Eurasian minnow, chub, and gudgeon *Gobio gobio*.

4.6. Correlation analysis results

The relative abundance of 7 fish species and the proportion of individuals of intermediate tolerance to habitat degradation and psammophilic ecological guilds correlated with single indicators of HPP performance during the winter, autumn, or spring bio-periods or with annual mean values. However, in 7 out of 10 cases, the relative abundance of any fish species correlated with any of the 7 HPP performance indicators in different bio-periods. In the remaining 3 cases, it was accompanied by a proportion of individuals of any of the above-mentioned ecological guilds. During the summer bio-period, fish metrics representing the number of species or the proportion of individuals of 6 ecological guilds and the proportion of individuals of only 3 species correlated with the indicators of HPP activity. The relative abundance of individuals of different species was related to different indicators of HPP performance, as in other bio-periods. Guild indicators were related to either the average duration of the pulse fall (5 indicators) or the average duration of the pulse rise (3 indicators). Analysis of the residual plots for all 14 fish indicators showed that the variance of the residuals was constant for only 5 indicators, four of which correlated with the mean duration of pulse rise or fall in the summer bio-period: the number of lithophilic fish species, which correlated with both average rise and fall duration, the number of rheoparous fish species, which correlated with pulse fall duration, and the proportion of individuals that were moderately tolerant to habitat degradation, and the percentage of stone loach, which correlated with the pulse rise duration. The latter two metrics were interrelated as the stone loach belongs to the medium tolerance guild. Only the proportion of individuals of the psammophilic ecological guild correlated with the pulse amplitude during the winter bio-period.

The correlation analysis was repeated between fish metrics, the HPP multimetric, and the distance between HPP and the modelled IH for the whole community. None of the fish metrics correlated with the HPP multimetric of HPP functioning in the winter, spring, and autumn bio-periods as well as with the annual average. However, the proportion of individuals of the habitat degradation intolerant, phytolithophilic, eurytopic, and rheophilic ecological guilds was significantly correlated with the HPP multimetric of the summer bio-period and the modelled IH

Table 7

Fish metrics that correlated (both Pearson and Spearman $R^2 \geq 0.91$, $p < 0.05$) with HPP multimetric of summer bio-period and the whole community IH, or distance between HPPs (N % - the proportion of individuals, NbSp – number of species; guilds: Hab – habitat, Habdeg – habitat degradation, Rep – reproduction). Only Pearson R data are presented. Significant correlations are shown in bold. An asterisk indicates correlations that were not considered significant due to inconsistency in residual variance.

Fish metric	HPP multimetric	IH	Distance
Habdeg intolerant (N %)	**0.93**	**0.93**	0.85
Habdeg intolerant (NbSp)	0.76	0.77	**0.95**
Habdeg tolerant (N %)	−0.87	−0.87	**−0.93**
Hab rheophilic (N %)	**0.92**	**0.92**	0.92*
Hab rheophilic (NbSp)	0.57	0.58	**0.97**
Hab eurytopic (N %)	**−0.92**	**−0.92**	−0.92*
Rep phytolithophilic (N %)	**−0.91**	**−0.92**	−0.93*
Rep psammophilic (N %)	0.81	0.84	0.96*
Chub (N %)	0.64	0.66	**0.96**

Table 6

ISH and ITH values for modelled fish species, and IH values for the whole community. Minimum ISH or ITH values, used to derive the whole community IH are indicated in bold. An asterisk indicates diadromous species not used to derive the whole community IH.

	Kulšėnai HPP		Renavas HPP		Vadagiai HPP		Ukrinai HPP		Juodeikiai HPP	
	ISH	ITH	ISH	ITH	ISH	ITH	ISH	ITH	ISH	ITH
Cottus gobio	0.92	0.97	0.92	0.85	0.76	0.81	0.85	0.63	0.96	**0.77**
Squalius cephalus	0.97	0.95	0.76	**0.51**	0.81	0.83	0.88	0.63	0.95	**0.77**
Leuciscus leuciscus	0.87	0.95	0.89	0.8	0.86	0.73	0.92	0.7	0.98	0.88
Gobio gobio	0.96	0.95	0.92	**0.51**	0.92	0.81	0.96	0.68	0.98	0.83
Phoxinus phoxinus	0.98	0.95	0.77	**0.51**	0.82	0.73	0.88	**0.61**	0.98	0.92
Alburnoides bipunctatus	**0.86**	0.97	0.63	**0.51**	**0.65**	0.73	0.8	0.8	0.86	0.83
Barbatula barbatula	0.99	0.95	0.94	0.84	0.98	0.82	0.96	0.63	1	0.86
*Salmo salar (juv.)**									0.88	0.73
*Salmo trutta (juv.)**									0.99	0.93
*Vimba vimba**									0.79	0.83
Whole community IH	0.86		0.51		0.65		0.61		0.77	

values (Table 7). The latter three fish metrics, the proportion of individuals of the habitat degradation tolerant and psammophilic guilds, the number of species of habitat degradation intolerant and rheophilic guilds as well as the relative abundance of chub correlated with the distance available for riverine fish downstream of the HPPs. However, the residual variance was inconsistent in the regression between the distance metric and the proportion of individuals of the psammophilic guild, as well as for all fish metrics, which also correlated with HPP multimetric in the summer bio-period. Finally, neither IH nor HPP multimetric correlated with the distance between HPPs, but there was an almost linear relationship between the modelled whole community IH values and the HPP multimetric of the summer bio-period ($R^2 > 0.99$, $p < 0.01$).

Each HPP in the Varduva River hydropower cascade had different combinations of main factors affecting the fish community. Different operating regimes of HPPs resulted in different proportions of individuals of intolerant, rheophilic, eurytopic, and phytolithophilic ecological guilds. The latter fact was confirmed by a significant correlation of these fish metrics with the modelled IH values, which depended solely on the HPP operation. The distance between HPPs determined the number of intolerant and rheophilic guild species as well as the relative abundance of chub and the proportion of individuals of habitat degradation tolerant guild. The overall results also indicated that a greater distance of river stretches available to riverine fish mitigated the effects of HPP operation, while the shutdown of HPP operation during a critical bio-period mitigated the effects of the reduction in suitable habitat area (Fig. 9).

5. Discussions

The operation of hydropower plants has a significant impact on runoff which exceeds the impact of climate change (Haddeland et al., 2014; Arheimer et al., 2017; Xiao et al., 2019; Maskey et al., 2022). In the case of a hydropower cascade, the negative impact on the river is even stronger because of cumulative or combined effects (European Commission…, 2018). And while there are many studies on the various impacts of single hydropower plants, significantly fewer studies were found that focused on the ecological effects of cascades of hydropower plants, which divide the river and disrupt its continuity multiple times (Ding et al., 2018; Lai et al., 2022; Sun et al., 2022). Although the Varduva River is regulated by five small hydropower plants, there has been no hydrological monitoring for a while. The absence of monitoring data downstream of each HPP in the cascade is a relatively common phenomenon (Wang et al., 2018; Xiao et al., 2019; Figueiredo et al.,

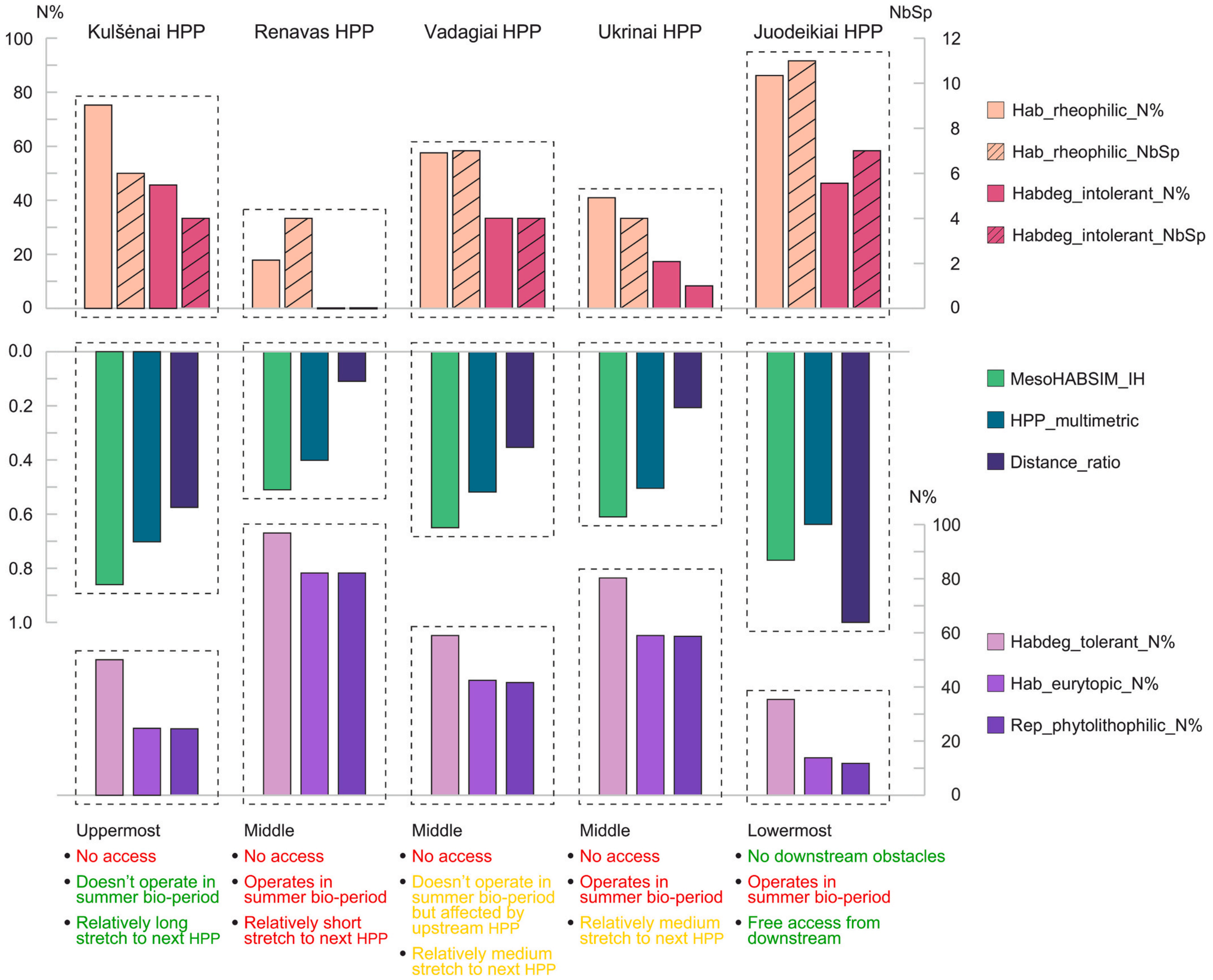

Fig. 9. Impact of each HPP in hydropower cascade on fish metrics and its causality (red factor – high impact, yellow factor – medium impact, green factor – low impact).

2021; Lai et al., 2022) and results in a loss of valuable information for further analysis. This issue is particularly relevant for hydropower cascade where all HPPs interact with each other and determine the river runoff characteristics within and downstream the cascade. In the Varduva River, the hydropower cascade of five HPPs forms a unique cascade structure where each of its units redistributes river runoff individually. Such complex regulation creates environmental problems related to sharing of runoff with downstream HPPs. High fluctuations in the water level are inevitable, especially in the cascade of five HPPs. The lack of available hydrological data on the operation of hydropower cascade led to the collection of water level data at 15-minute intervals. The practical application of water level loggers and hydrological techniques such as discharge measurements and water level-discharge rating curves enabled to create discharge data series for the ungauged river (Pool and Seibert, 2021). The collected hydrological data of the Varduva River revealed that the river stretches downstream of each power plant were affected by hydropeaking, which is one of the main drivers of physical and ecological changes in regulated rivers (Batalla et al., 2021; Halleraker et al., 2022). The intensity and timing of hydropeaking varied at each location downstream of the HPPs, depending on factors such as the operating mode of the HPP, turbine characteristics, and reservoir volume. Therefore, different flow regimes were observed throughout the year downstream of each facility, indicating a complex interaction between power plants based on water-use competition along the cascade.

Downstream of Renavas HPP (second in the cascade), there was many cases of a drastic decrease in discharge, leading to violations of the defined environmental discharge. This indicates that the operation of the HPPs in the cascade had a significant negative impact on downstream river flow. During the observation period, a dramatic increase of low pulse cases and total duration of low pulses (compared to the natural flow regime upstream of the hydropower cascade) were estimated in all studied dammed river stretches. The high amount of low and high pulse cases was closely related to the HPPs (e.g., Kulšėnai and Ukrinai) ability to operate in a wide range of discharge amplitude, especially during the low flow. HPPs with relatively large reservoir volumes and a high lower boundary limit of turbine discharge (e.g., Renavas and Juodeikiai) induced more prolonged average durations of low and high pulses during accumulation and release. This highlights the importance and role of reservoir characteristics in transforming the flow regime. The cumulative impact of multiple HPPs in the cascade was found to be significantly greater than the impact of single HPPs, leading to considerable changes in the characteristics of low and high pulses in the river since downstream-located HPPs are affected by the upstream ones. The most considerable changes in the characteristics of low and high pulses were also estimated for individual HPPs in Lithuania (Šarauskienė et al., 2021). Timpe and Kaplan (2017) assessed the impacts of single versus multiple dams and found that the cumulative impact was also significantly higher for the frequency and duration of high and low pulses than the impact of single dams. Similarly, Ely et al. (2020) revealed that downstream of the studied hydropower cascade, the number of low pulses increased in some cases by more than five times. In contrast, Figueiredo et al. (2021) estimated that there were no significant differences in the percentage of indicators of hydrologic alteration when they compared river reaches with more than one hydropower facility to those with one HPP, and therefore stated that there was no evidence of cumulative effects. Unfortunately, there is a lack of research on the cumulative impact of HPPs cascade on the river ecosystem (Sun et al., 2022). Timpe and Kaplan (2017) suggested that additional studies are necessary to elucidate the potential influences of different dam sizes, types, and climate regions on the accumulative effects of multiple dams. The present study revealed that the highest degree of flow alteration was detected downstream of the smallest HPP reservoirs, while larger reservoirs mitigated the upstream flow changes, but at the same time caused individual alterations produced by their own operation regime.

61 of 70 studies reviewed by Lloyd et al. (2004) demonstrated ecological and/or geomorphological effects on spatial changes in physical habitats associated with flow modification. Unnatural fluctuations in regulated river water levels and altered discharge were also directly responsible for the transformation of GUs. In the present study, the greatest number of different GUs was identified in the river stretch downstream of the last HPP. The altered river flow caused by hydropower cascades leads to changes in the species composition, distribution, and activity patterns of aquatic organisms (Sun et al., 2022). In the study on the main negative environmental impacts of small hydropower plants, habitat deterioration was ranked first (Başkaya et al., 2011), while the lower hydromorphological diversity makes aquatic organisms more sensitive to the impacts of HPP under climate change (Akstinas et al., 2021). HPP induced alteration of timing, duration, frequency, and rate of flow changes are well known characteristics that have specific effects on aquatic organisms (Greimel et al., 2018). However, the interaction of different types of deviations from the natural hydrological regime resulting from the operation of HPPs can amplify or mitigate the overall impact. The differences between the HPPs with respect to individual but different indicators might be the reason why the search for the response of fish metrics to individual HPP performance indicators in the Varduva River hydropower cascade did not yield good results. The HPP multimetric of the summer bio-period showed a better ability to discriminate changes in fish metrics, thus confirming that multimetric pressure indices are reflecting the integrated effects of different pressures and may be better predictors of changes in fish communities than individual pressures (Lepage et al., 2016; Poikane et al., 2017). The absence of significant relationships with the HPP multimetric of other bio-periods may be explained by the difference in the water quantity during the low pulses. The average discharge of the low pulse below the HPPs of the highest impact during the summer bio-period was at least twice smaller than the closest values of the other bio-periods. In exceptional cases, such as at Renavas HPP, the average discharge of the low pulse during the summer bio-period was 14 times smaller than the second smallest average value recorded during the spring spawning bio-period. Comparing the other bio-periods, the differences were even larger. All this confirms that the negative effects of HPP are the greatest in the low flow season (Loures and Pompeu, 2015).

The HPP multimetric of the summer bio-period also significantly correlated with IH values, which, although calculated by modelling the availability of suitable habitat rather than fish metrics, are also based on an integrated assessment of the temporal and spatial changes due to HPP operation (Parasiewicz et al., 2013). Meanwhile, the ecological guilds, which aggregate species with similar ecological requirements into larger units and form an operational unit that links the characteristics of individual species to the community as a whole (Noble et al., 2007), have shown a more pronounced response to cumulative effects of the HPPs in the present study than individual fish species. Among them, the guild of species intolerant of habitat degradation is represented by species that are most sensitive to any deviation of their habitat from natural conditions. The rheophilic and eurytopic guilds, both of which have shown a response to the overall impact of the HPP, are inversely correlated, as both accounted for 99.9–100 % of the total number of individuals in the studied stretches of the Varduva River. The shift from a dominance of species preferring habitats with running water to species that are also tolerant of stagnant water indicates a greater resilience of flow-indifferent species to the permanent changes in the hydrological regime caused by HPP. The phytolitophilic guild, the proportion of individuals of which is also significantly correlated with the HPP multimetric, is almost exclusively represented in the Varduva River by the roach *Rutilus rutilus*, the bleak *Alburnus alburnus* and the perch, whose relative abundance in the stretches of the Lithuanian rivers impacted by the HPPs has been previously found to be significantly higher in comparison to the strethes of the natural hydrological regime (Virbickas et al., 2020). The results of this study confirm the relatively higher tolerance of these species to the effects of HPPs, as their overall proportion of individuals in the community increases with increasing HPPs pressure.

The length of the unimpounded stretch of river between HPP dams is an equally important factor structuring the fish community (Wang et al., 2011; Musil et al., 2012; Van Treeck et al., 2022). In contrast to the effects of the HPP performance, the number of species, rather than the proportions of individuals in the habitat degradation intolerant and rheophilic guilds, was correlated with the distance between the HPP dams in the Varduva River. The serial discontinuity concept (Ward and Stanford, 1983) predicts that the influence of impoundment on ecological parameters decreases with increasing discontinuity distance. It has already been shown that overall fish diversity below the dam increases in the downstream direction to the next impoundment (Freedman et al., 2014). This implies that the longer the stretch of the river below the HPP, the more opportunities for riverine fish to find a sufficient habitat that ensures the persistence of their populations and from which recolonisation can take place, thus supporting a greater diversity of HPP sensitive species. The distance between the dams also determined the relative abundance of rheophilic chub, which was present in all studied stretches of the Varduva River. The chub has greater environmental plasticity than typical riverine fish (Carrel and Rivier, 1996; Arlinghaus and Wolter, 2003), and no significant differences were previously detected in the relative abundance of this species in river stretches affected by HPP operation compared with stretches of natural hydrology (Virbickas et al., 2020). However, chub is the largest, long-lived rheoparous species in the Varduva River, and thus it is likely to be more limited by the amount of available habitat for adult (Halpern et al., 2005) than smaller, shorter-lived fish species with similar resilience to HPP operation. The inverse dependence of another fish metric, i.e., the proportion of fish tolerating habitat degradation, on the distance between dams, may be related to the ratio of lentic and lotic habitats. Most of the tolerant species found in the Varduva River can live and spawn in both the river and the reservoir. Migration from the reservoir can permanently supplement populations in the river upstream (Hladík and Kubečka, 2003) thus supporting a relatively higher overall abundance of tolerant species in the stretches between the HPP dams.

In this study, HPP operation metrics were continuously measured for only one year. However, a comparison with the data from the fish monitoring that was carried out below the 3 HPPs in 2014–2015 and 2022 suggests that the HPP operation pattern should have been similar over a longer period. Despite the different years and locations of the monitoring, the proportion of individuals and the number of species in the ecological guilds, which were significantly correlated with the HPP multimetric and the distance between dams in the present study, followed generally the same pattern in the fish monitoring data. The only difference was observed in 2015 when two intolerant species (bullhead and Eurasian minnow) were still present in the area downstream of the Renavas HPP. However, they were no longer found in 2021 and 2022. Vadagiai HPP, installed in 2004, significantly reduced the suitable habitat for rheophilic fish below the Renavas HPP by shortening the unimpounded river section from 14 km to 2.9 km. Mentioned reduction in suitable habitats is likely have led the complete extinction of these intolerant species 17 years after the installation of Vadagiai HPP as an additional migration barrier.

This study focused on the processes within a cascade of HPPs, rather than on the combined effects of all HPPs. Based on the cumulative impact assessment framework proposed by Van Treeck et al. (2022), the overall impact of the HPP cascade on the ecosystem of the Varduva River should be classified as high. Although habitat fragmentation due to barriers is relatively low (relative barrier density < 0.5 barriers/km), the total length of the impounded stretches covers more than a third (37 %) of the total length of the river in the hydropower cascade, which significantly reduces the total area of habitat for rheophilic species. None of the HPP dams have fish ladders or bypasses, thus completely preventing upstream migration of fish and significantly hindering downstream migration. Most of the HPPs only use vertical fish screens with a 35 mm spacing between the vertical bars, exclusively 45 mm fish protection screen is installed at Renavas HPP. Even for such fish species as European perch and roach, the adults up to 34 and 23 cm respectively may pass through the vertical fish protection screens with a bar spacing of 20 mm (Knott et al., 2023). The lack of efficient installations to ensure safe downstream migration increases the probability of fish mortality in turbines. The Renavas HPP is likely to cause the highest fish mortality. This HPP not only has the largest bar spacing, but also the highest ratio between installed and mean discharge, and one of the highest barrier heights, all of which increase the hazard to fish (Van Treeck et al., 2021). Fish mortality also depends on other factors and may vary in the wide range between the study sites despite the same type of turbine (Mueller et al., 2022). The results of this study allowed to identify the most critical locations in the HPP cascade in terms of hydrological regime alteration and habitat fragmentation. However, given that fish migration is severely hampered and there is a high risk of HPP induced mortality, the ecological status of the Varduva River can only be substantially improved through a combination of measures to optimise the operation of the HPP and to facilitate fish migration.

Overall, this study confirms the importance of continuous hydrological monitoring to understand and manage the environmental impacts of hydropower plants on river ecosystems. It demonstrates the necessity to assess all patterns of hydrological alterations caused by HPP and their cumulative effect, rather than single HPP performance indicators. The HPP multimetric is proved to be a useful tool for comparing the impacts of HPPs on fish communities within a hydropower cascade. It not only considers the gradient of values of the same metrics within the hydropower cascade but also takes into account the extremes of different specific metrics at different HPPs. This approach could also be used for a comparative assessment and initial overview of the impacts of HPPs located not only in lowland rivers whose basins cover a large part of Europe (Rivers of Europe, 2022), but also in rivers with different physico-geographical features. Moreover, the application of the HPP multimetric is not limited to similar fishes as it could also be tested with other communities under natural and altered conditions. The significant correlation between the HPP multimetric and IH suggests that the HPP multimetric reflects similar aspects of HPP impact estimated by the mesohabitat modelling. In addition, the HPP multimetric has the advantage of a much lower computation workload compared to the more complex and time-consuming MesoHABSIM method. However, HPP multimetric, as described in this study, only assesses the relative impact of different HPPs within the cascade and can be used to prioritize the order of HPPs for impact mitigation or for comparative purposes. For a direct assessment, where absolute impact needs to be evaluated, the natural flow parameters should be used as a reference for the calculation of the HPP multimetric. The study also highlights the importance of assessing other factors that may act in combination with hydrological changes caused by HPPs thus resulting in cumulative hazard to fish induced by a particular HPP (Van Treeck et al., 2021). However, it also shows the importance and need of more research to better understand the mechanisms of such combined effects on the structuring of fish communities in the HPP cascade.

6. Conclusions

This study highlighted the importance of continuous assessment of the operation of each hydropower plant in the cascade, especially in the ungauged rivers where comprehensive control measures are not implemented through monitoring. The evaluation of changes in the magnitude, timing, frequency, and rate of altered flow under the operation of HPP allows us to understand the interaction between HPPs and to identify the crucial elements of the HPP operation whose impacts are the most significant and which should be mitigated as a priority.

The operating regime revealed the relationship between the indicators of hydrologic alterations and the technical characteristics of installed turbines and reservoir volume. The HPPs with small reservoir volume and turbines with wide discharge amplitude (especially with small lower boundary) induced the largest amount of low and high pulses in the river. Despite being able to operate with relatively small discharge, these HPPs still caused significant flow alterations. On the other hand, the HPPs with the largest volume reservoir and relatively high lower boundary of turbine discharge produced a lower amount of pulsations downstream of HPP. However, the duration of extreme boundary conditions was prolonged due to the ability of reservoir volume to accumulate more water and release for more effective usage of the mentioned HPPs.

The results indicate three key elements of the hydropower cascade, namely, the operating regime of the HPP, the seasonality of operation, and the distance between dams, which determine the structure and species composition of fish community within the cascade. A greater distance of river stretches available to riverine fish between dams mitigates the effects of HPP operation, while the shutdown of HPP during a critical bio-period mitigates the effects of a reduction in the area of suitable habitat. These interactions should be considered when designing mitigation measures that optimise the balance between fish community needs and electricity production.

The HPP multimetric approach combines relative values of various indicators that represent different aspects of HPP performance into a single numerical expression. This comprehensive approach allows reflecting not only the gradient of values of the same metrics within the hydropower cascade but also the extremes of values of different specific metrics at different HPPs. The HPP multimetric significantly correlates with fish metrics and the IH index, which was estimated using a complex habitat modelling approach. This relationship demonstrates the potential of HPP multimetric as a relatively inexpensive and simple tool for assessing the integrated impact of consecutive HPPs that form a cascade in a river.

Ethical statement

Fish sampling was carried out in accordance with the ethical requirements described in EU Directive 2010/63/EU and the European Standard CEN EN 14011:2003 "Water quality – Sampling of fish with electricity". All fish caught remained healthy and alive and were released immediately after species identification and counting. The permit to sample fish with electric fishing gear was issued by the Lithuanian Environmental Protection Agency (permit No. 026, issued on July 21, 2021).

CRediT authorship contribution statement

Vytautas Akstinas: Conceptualization, Methodology, Writing – original draft, Visualization. **Tomas Virbickas:** Conceptualization, Methodology, Writing – original draft, Writing – review & editing. **Diana Meilutytė-Lukauskienė:** Validation, Writing – original draft, Writing – review & editing. **Diana Šarauskienė:** Writing – original draft, Writing – review & editing. **Paolo Vezza:** Software, Writing – review & editing. **Jūratė Kriaučiūnienė:** Conceptualization, Writing – review & editing. **Vytautas Rakauskas:** Investigation, Data curation, Writing – original draft. **Andrius Steponėnas:** Formal analysis, Data curation, Validation. **Aldona Jurgelėnaitė:** Data curation, Writing – original draft. **Darius Jakimavičius:** Investigation, Data curation, Formal analysis. **Serhii Nazarenko:** Investigation, Data curation, Writing – original draft.

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.

Data availability

The data that support the findings of this study are available from the paper authors upon reasonable request.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.scitotenv.2023.167541.

References

Abbasi, T., Abbasi, S.A., 2011. Small hydro and the environmental implications of its extensive utilization. Renew. Sust. Energ. Rev. 15, 2134–2143. https://doi.org/10.1016/j.rser.2010.11.050.

Acreman, M.C., Dunbar, M.J., 2004. Defining environmental river flow requirements – a review. Hydrol. Earth Syst. Sci. 8, 861–876. https://doi.org/10.5194/hess-8-861-2004.

Acreman, M.C., Overton, I.C., King, J., Wood, P.J., Cowx, I.G., Dunbar, M.J., Kendy, E., Young, W.J., 2014. The changing role of ecohydrological science in guiding environmental flows. Hydrol. Sci. J. 59, 433–450. https://doi.org/10.1080/02626667.2014.886019.

Adamczyk, M., Parasiewicz, P., Vezza, P., Prus, P., De Cesare, G., 2019. Empirical validation of MesoHABSIM models developed with different habitat suitability criteria for bullhead *Cottus gobio* L. as an indicator species. Water 11, 726. https://doi.org/10.3390/w11040726.

Akstinas, V., Virbickas, T., Kriaučiūnienė, J., Šarauskienė, D., Jakimavičius, D., Rakauskas, V., Negro, G., Vezza, P., 2021. The combined impact of hydropower plants and climate change on river runoff and fish habitats in lowland watersheds. Water 13, 3508. https://doi.org/10.3390/w13243508.

Anderson, D., Moggridge, H., Warren, P., Shucksmith, J., 2015. The impacts of 'run-of-river' hydropower on the physical and ecological condition of rivers: physical and ecological impacts of ROR hydropower. Water Environ. J. 29, 268–276. https://doi.org/10.1111/wej.12101.

Arheimer, B., Donnelly, C., Lindström, G., 2017. Regulation of snow-fed rivers affects flow regimes more than climate change. Nat. Commun. 8, 62. https://doi.org/10.1038/s41467-017-00092-8.

Arlinghaus, R., Wolter, C., 2003. Amplitude of ecological potential: chub *Leuciscus cephalus* (L.) spawning in an artificial lowland canal. J. Appl. Ichthyol. 19, 52–54. https://doi.org/10.1046/j.1439-0426.2003.00343.x.

Athayde, S., Duarte, C.G., Gallardo, A.L.C.F., Moretto, E.M., Sangoi, L.A., Dibo, A.P.A., Siqueira-Gay, J., Sánchez, L.E., 2019. Improving policies and instruments to address cumulative impacts of small hydropower in the Amazon. Energy Policy 132, 265–271. https://doi.org/10.1016/j.enpol.2019.05.003.

Bakrač, S., Marković, V., Drobnjak, S., Đorđević, D., Stamenković, N., 2021. Using historical aerial photography for monitoring of environment changes: a case study of Bovan lake, eastern Serbia. J. Environ. Eng. Landsc. Manag. 29, 305–317. https://doi.org/10.3846/jeelm.2021.15567.

Başkaya, Ş., Başkaya, E., Sari, A., 2011. The principal negative environmental impacts of small hydropower plants in Turkey. Afr. J. Agric. Res. 6, 3284–3290. https://doi.org/10.5897/AJAR10.786.

Batalla, R.J., Gibbins, C.N., Alcázar, J., Brasington, J., Buendia, C., Garcia, C., Llena, M., López, R., Palau, A., Rennie, C., Wheaton, J.M., Vericat, D., 2021. Hydropeaked rivers need attention. Environ. Res. Lett. 16, 021001 https://doi.org/10.1088/1748-9326/abce26.

Bechter, T., Baumann, K., Birk, S., Bolik, F., Graf, W., Pletterbauer, F., 2018. LaRiMo - a simple and efficient GIS-based approach for large-scale morphological assessment of large European rivers. Sci. Total Environ. 628–629, 1191–1199. https://doi.org/10.1016/j.scitotenv.2018.02.084.

Belletti, B., Rinaldi, M., Bussettini, M., Comiti, F., Gurnell, A.M., Mao, L., Nardi, L., Vezza, P., 2017. Characterising physical habitats and fluvial hydromorphology: a new system for the survey and classification of river geomorphic units. Geomorphology 283, 143–157. https://doi.org/10.1016/j.geomorph.2017.01.032.

Carolli, M., Garcia De Leaniz, C., Jones, J., Belletti, B., Huđek, H., Pusch, M., Pandakov, P., Börger, L., Van De Bund, W., 2023. Impacts of existing and planned hydropower dams on river fragmentation in the Balkan Region. Sci. Total Environ. 871, 161940. https://doi.org/10.1016/j.scitotenv.2023.161940.

Carrel, G., Rivier, B., 1996. Distribution of three euryoecious cyprinids in the main channel of the Lower River Rhone. rs 10, 363–374. https://doi.org/10.1127/lr/10/1996/363.

Clapuyt, F., Vanacker, V., Van Oost, K., 2016. Reproducibility of UAV-based earth topography reconstructions based on structure-from-motion algorithms. Geomorphology 260, 4–15. https://doi.org/10.1016/j.geomorph.2015.05.011.

Clarke, K.D., Pratt, T.C., R., G., Scrutton, D.A., Smokorowski, K.E., 2008. Validation of the flow management pathway: effects of altered flow on fish habitat and fishes downstream from a hydropower dam. In: Canadian Technical Report of Fisheries and Aquatic Sciences 2784. Fisheries and Oceans Canada, St. John's NL.

Couto, T.B., Olden, J.D., 2018. Global proliferation of small hydropower plants - science and policy. Front. Ecol. Environ. 16, 91–100. https://doi.org/10.1002/fee.1746.

Ding, Z., Fang, G., Wen, X., Tan, Q., Huang, X., Lei, X., Tian, Y., Quan, J., 2018. A novel operation chart for cascade hydropower system to alleviate ecological degradation in hydrological extremes. Ecol. Model. 384, 10–22. https://doi.org/10.1016/j.ecolmodel.2018.05.025.

Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for community action in the field of water policy, 2000 (OJ L).

Ely, P., Fantin-Cruz, I., Tritico, H.M., Girard, P., Kaplan, D., 2020. Dam-induced hydrologic alterations in the rivers feeding the Pantanal. Front. Environ. Sci. 8, 579031. https://doi.org/10.3389/fenvs.2020.579031.

European Commission. Directorate General for the Environment, 2018. Guidance on the Requirements for Hydropower in Relation to EU Nature Legislation. Publications Office, LU.

European Commission. Joint Research Centre. Institute for Environment and Sustainability, 2009. Water framework directive intercalibration: technical report. In: Part 1, Rivers. Publications Office, LU.

Fensham, R.J., Fairfax, R.J., 2002. Aerial photography for assessing vegetation change: a review of applications and the relevance of findings for Australian vegetation history. Aust. J. Bot. 50, 415. https://doi.org/10.1071/BT01032.

Figueiredo, J.S.M.C.D., Fantin-Cruz, I., Silva, G.M.S., Beregula, R.L., Girard, P., Zeilhofer, P., Uliana, E.M., Morais, E.B.D., Tritico, H.M., Hamilton, S.K., 2021. Hydropeaking by small hydropower facilities affects flow regimes on tributaries to the Pantanal wetland of Brazil. Front. Environ. Sci. 9, 577286. https://doi.org/10.3389/fenvs.2021.577286.

Freedman, J.A., Lorson, B.D., Taylor, R.B., Carline, R.F., Stauffer, J.R., 2014. River of the dammed: longitudinal changes in fish assemblages in response to dams. Hydrobiologia 727, 19–33. https://doi.org/10.1007/s10750-013-1780-6.

Gailiušis, B., Jablonskis, J., Kovalenkovienė, M., 2001. Lithuanian Rivers: Hydrography and Runoff. Lithuanian Energy Institute, Kaunas, Lithuania.

Gajbhiye, S., Sharma, S.K., Awasthi, M.K., 2015. Application of principal components analysis for interpretation and grouping of water quality parameters. IJHIT 8, 89–96. https://doi.org/10.14257/ijhit.2015.8.4.11.

Gao, Y., Vogel, R.M., Kroll, C.N., Poff, N.L., Olden, J.D., 2009. Development of representative indicators of hydrologic alteration. J. Hydrol. 374, 136–147. https://doi.org/10.1016/j.jhydrol.2009.06.009.

Gibeau, P., Connors, B.M., Palen, W.J., 2017. Run-of-River hydropower and salmonids: potential effects and perspective on future research. Can. J. Fish. Aquat. Sci. 74, 1135–1149. https://doi.org/10.1139/cjfas-2016-0253.

Greimel, F., Schülting, L., Graf, W., Bondar-Kunze, E., Auer, S., Zeiringer, B., Hauer, C., 2018. Hydropeaking impacts and mitigation. In: Schmutz, S., Sendzimir, J. (Eds.), Riverine Ecosystem Management. Springer International Publishing, Cham, pp. 91–110. https://doi.org/10.1007/978-3-319-73250-3_5.

Guo, Y., Zhang, Y., Zhang, L., Wang, Z., 2021. Regionalization of hydrological modeling for predicting streamflow in ungauged catchments: a comprehensive review. WIREs Water 8. https://doi.org/10.1002/wat2.1487.

Haddeland, I., Heinke, J., Biemans, H., Eisner, S., Flörke, M., Hanasaki, N., Konzmann, M., Ludwig, F., Masaki, Y., Schewe, J., Stacke, T., Tessler, Z.D., Wada, Y., Wisser, D., 2014. Global water resources affected by human interventions and climate change. Proc. Natl. Acad. Sci. U. S. A. 111, 3251–3256. https://doi.org/10.1073/pnas.1222475110.

Halleraker, J.H., Kenawi, M.S., L'Abée-Lund, J.H., Bakken, T.H., Alfredsen, K., 2022. Assessment of flow ramping in water bodies impacted by hydropower operation in Norway – is hydropower with environmental restrictions more sustainable? Sci. Total Environ. 832, 154776. https://doi.org/10.1016/j.scitotenv.2022.154776.

Halpern, B.S., Gaines, S.D., Warner, R.R., 2005. Habitat size, recruitment, and longevity as factors limiting population size in stage-structured species. Am. Nat. 165, 82–94. https://doi.org/10.1086/426672.

Hanks, R.D., Kanno, Y., Rash, J.M., 2018. Can single-pass electrofishing replace three-pass depletion for population trend detection? Trans. Am. Fish. Soc. 147, 729–739. https://doi.org/10.1002/tafs.10061.

Hladík, M., Kubečka, J., 2003. Fish migration between a temperate reservoir and its main tributary. Hydrobiologia 504, 251–266. https://doi.org/10.1023/B:HYDR.0000008525.46939.42.

Kabi, J.N., Wa Maina, C., Mharakurwa, E.T., Mathenge, S.W., 2023. Low cost, LoRa based river water level data acquisition system. HardwareX 14, e00414. https://doi.org/10.1016/j.ohx.2023.e00414.

Kallis, G., Butler, D., 2001. The EU water framework directive: measures and implications. Water Policy 3, 125–142. https://doi.org/10.1016/S1366-7017(01)00007-1.

Kelly-Richards, S., Silber-Coats, N., Crootof, A., Tecklin, D., Bauer, C., 2017. Governing the transition to renewable energy: a review of impacts and policy issues in the small hydropower boom. Energy Policy 101, 251–264. https://doi.org/10.1016/j.enpol.2016.11.035.

Khan, M.S.I., Ohlemüller, R., Maloney, R.F., Seddon, P.J., 2021. Monitoring dynamic braided river habitats: applicability and efficacy of aerial photogrammetry from manned aircraft versus unmanned aerial systems. Drones 5, 39. https://doi.org/10.3390/drones5020039.

Knehtl, M., Petkovska, V., Urbanič, G., 2018. Is it time to eliminate field surveys from hydromorphological assessments of rivers?-Comparison between a field survey and a remote sensing approach. Ecohydrology 11, e1924. https://doi.org/10.1002/eco.1924.

Knott, J., Mueller, M., Pander, J., Geist, J., 2023. Bigger than expected: species- and size-specific passage of fish through hydropower screens. Ecol. Eng. 188, 106883. https://doi.org/10.1016/j.ecoleng.2022.106883.

Korman, J., Campana, S.E., 2009. Effects of hydropeaking on nearshore habitat use and growth of age-0 rainbow trout in a large regulated river. Trans. Am. Fish. Soc. 138, 76–87. https://doi.org/10.1577/T08-026.1.

Koutrakis, E.T., Triantafillidis, S., Sapounidis, A.S., Vezza, P., Kamidis, N., Sylaios, G., Comoglio, C., 2019. Evaluation of ecological flows in highly regulated rivers using the mesohabitat approach: a case study on the Nestos River, N. Greece. Ecohydrol. Hydrobiol. 19, 598–609. https://doi.org/10.1016/j.ecohyd.2018.01.002.

Kuriqi, A., Pinheiro, A.N., Sordo-Ward, A., Bejarano, M.D., Garrote, L., 2021. Ecological impacts of run-of-river hydropower plants—current status and future prospects on the brink of energy transition. Renew. Sust. Energ. Rev. 142, 110833. https://doi.org/10.1016/j.rser.2021.110833.

Lai, R., Chen, X., Zhang, L., 2022. Evaluating the impacts of small cascade hydropower from a perspective of stream health that integrates eco-environmental and hydrological values. J. Environ. Manag. 305, 114366. https://doi.org/10.1016/j.jenvman.2021.114366.

Lake, P.S., 2000. Disturbance, patchiness, and diversity in streams. J. N. Am. Benthol. Soc. 19, 573–592. https://doi.org/10.2307/1468118.

Lange, K., Meier, P., Trautwein, C., Schmid, M., Robinson, C.T., Weber, C., Brodersen, J., 2018. Basin-scale effects of small hydropower on biodiversity dynamics. Front. Ecol. Environ. 16, 397–404. https://doi.org/10.1002/fee.1823.

Langhammer, J., Lendzioch, T., Miřijovský, J., Hartvich, F., 2017. UAV-based optical granulometry as tool for detecting changes in structure of flood depositions. Remote Sens. 9, 240. https://doi.org/10.3390/rs9030240.

Lepage, M., Harrison, T., Breine, J., Cabral, H., Coates, S., Galván, C., García, P., Jager, Z., Kelly, F., Mosch, E.C., Pasquaud, S., Scholle, J., Uriarte, A., Borja, A., 2016. An approach to intercalibrate ecological classification tools using fish in transitional water of the North East Atlantic. Ecol. Indic. 67, 318–327. https://doi.org/10.1016/j.ecolind.2016.02.055.

Li, B., Yang, L., Song, X., Diamantopoulos, E., 2023. Identifying surface water and groundwater interactions using multiple experimental methods in the riparian zone of the polluted and disturbed Shaying River, China. Sci. Total Environ. 875, 162616. https://doi.org/10.1016/j.scitotenv.2023.162616.

Linnansaari, T., Monk, W.A., Baird, D.J., Curry, R.A., 2012. Review of approaches and methods to assess environmental flows across Canada and internationally. In: Canadian Science Advisory Secretariat, Research Document 2012/039. Department of Fisheries and Oceans Canada, New Brunswick.

Lloyd, N., Quinn, G., Thoms, M., Arthington, A., Gawne, B., Humphries, P., Walker, K., 2004. Does flow modification cause geomorphological and ecological response in rivers? A literature review from an Australian perspective. In: Technical Report 1/2004, CRC for Freshwater Ecology, Canberra, Australia.

Loures, R.C., Pompeu, P.S., 2015. Seasonal and diel changes in fish distribution in a tropical hydropower plant tailrace: evidence from hydroacoustic and gillnet sampling. Fish. Manag. Ecol. 22, 185–196. https://doi.org/10.1111/fme.12116.

Manfreda, S., Pizarro, A., Moramarco, T., Cimorelli, L., Pianese, D., Barbetta, S., 2020. Potential advantages of flow-area rating curves compared to classic stage-discharge-relations. J. Hydrol. 585, 124752. https://doi.org/10.1016/j.jhydrol.2020.124752.

Maskey, M.L., Facincani Dourado, G., Rallings, A.M., Rheinheimer, D.E., Medellín-Azuara, J., Viers, J.H., 2022. Assessing hydrological alteration caused by climate change and reservoir operations in the San Joaquin River Basin, California. Front. Environ. Sci. 10, 765426. https://doi.org/10.3389/fenvs.2022.765426.

Mbaka, J.G., Wanjiru Mwaniki, M., 2015. A global review of the downstream effects of small impoundments on stream habitat conditions and macroinvertebrates. Environ. Rev. 23, 257–262. https://doi.org/10.1139/er-2014-0080.

McGarigal, K., Stafford, S., Cushman, S., 2000. Multivariate Statistics for Wildlife and Ecology Research. Springer New York, New York, NY. https://doi.org/10.1007/978-1-4612-1288-1.

Meile, T., Boillat, J.-L., Schleiss, A.J., 2011. Hydropeaking indicators for characterization of the Upper-Rhone River in Switzerland. Aquat. Sci. 73, 171–182. https://doi.org/10.1007/s00027-010-0154-7.

Meshram, S.G., Sharma, S.K., 2018. Application of principal component analysis for grouping of morphometric parameters and prioritization of watershed. In: Singh, V.P., Yadav, S., Yadava, R.N. (Eds.), Hydrologic Modeling, Water Science and Technology Library. Springer, Singapore, pp. 447–458. https://doi.org/10.1007/978-981-10-5801-1_31.

Mittal, N., Bhave, A.G., Mishra, A., Singh, R., 2016. Impact of human intervention and climate change on natural flow regime. Water Resour. Manag. 30, 685–699. https://doi.org/10.1007/s11269-015-1185-6.

Mueller, M., Knott, J., Pander, J., Geist, J., 2022. Experimental comparison of fish mortality and injuries at innovative and conventional small hydropower plants. J. Appl. Ecol. 59, 2360–2372. https://doi.org/10.1111/1365-2664.14236.

Musil, J., Horký, P., Slavík, O., Zbořil, A., Horká, P., 2012. The response of the young of the year fish to river obstacles: functional and numerical linkages between dams, weirs, fish habitat guilds and biotic integrity across large spatial scale. Ecol. Indic. 23, 634–640. https://doi.org/10.1016/j.ecolind.2012.05.018.

Niemi, G.J., DeVore, P., Detenbeck, N., Taylor, D., Lima, A., Pastor, J., Yount, J.D., Naiman, R.J., 1990. Overview of case studies on recovery of aquatic systems from disturbance. Environ. Manag. 14, 571–587. https://doi.org/10.1007/BF02394710.

Noble, R.A.A., Cowx, I.G., Goffaux, D., Kestemont, P., 2007. Assessing the health of European rivers using functional ecological guilds of fish communities: standardising species classification and approaches to metric selection. Fish. Manag. 14, 381–392. https://doi.org/10.1111/j.1365-2400.2007.00575.x.

Ozcan, O., Akay, S., 2018. Monitoring hydromorphological changes in meandering rivers via multi-temporal UAV-based measurements (other). Hydrology. https://doi.org/10.1002/essoar.10500241.1.

Parasiewicz, P., 2001. MesoHABSIM: a concept for application of instream flow models in river restoration planning. Fisheries 26, 6–13. https://doi.org/10.1577/1548-8446(2001)026<0006:M>2.0.CO;2.

Parasiewicz, P., 2004. Ecohydrology Study of the Quinebaug River—Final Report to the Project Management Committee and the New England Interstate Water Pollution Control Commission. Presented by the Instream Habitat Program and the NY Cooperative Fish & Wildlife Research Unit, Department of Natural Resources, Cornell University, Ithaca, NY.

Parasiewicz, P., 2007. The MesoHABSIM model revisited. River Res. Appl. 23, 893–903. https://doi.org/10.1002/rra.1045.

Parasiewicz, P., 2008. Application of MesoHABSIM and target fish community approaches to restoration of the Quinebaug River, Connecticut and Massachusetts, USA. River Res. Appl. 24, 459–471. https://doi.org/10.1002/rra.1064.

Parasiewicz, P., Rogers, J.N., Vezza, P., Gortázar, J., Seager, T., Pegg, M., Wiśniewolski, W., Comoglio, C., 2013. Applications of the MesoHABSIM simulation model. In: Maddock, I., Harby, A., Kemp, P., Wood, P. (Eds.), Ecohydraulics. John Wiley & Sons, Ltd, Chichester, UK, pp. 109–124. https://doi.org/10.1002/9781118526576.ch6.

Parasiewicz, P., Prus, P., Suska, K., Marcinkowski, P., 2018. "E = mc2" of environmental flows: a conceptual framework for establishing a fish-biological Foundation for a Regionally Applicable Environmental Low-Flow Formula. Water 10, 1501. https://doi.org/10.3390/w10111501.

Pardo-Loaiza, J., Solera, A., Bergillos, R.J., Paredes-Arquiola, J., Andreu, J., 2021. Improving indicators of hydrological alteration in regulated and complex water resources systems: a case study in the Duero River Basin. Water 13, 2676. https://doi.org/10.3390/w13192676.

Person, É., 2013. Impact of Hydropeaking on Fish and their Habitat. https://doi.org/10.5075/EPFL-THESIS-5812.

Petts, G.E., 2009. Instream flow science for sustainable river management. JAWRA J. Am. Water Resour. Assoc. 45, 1071–1086. https://doi.org/10.1111/j.1752-1688.2009.00360.x.

Poff, N.L., 2018. Beyond the natural flow regime? Broadening the hydro-ecological foundation to meet environmental flows challenges in a non-stationary world. Freshw. Biol. 63, 1011–1021. https://doi.org/10.1111/fwb.13038.

Poikane, S., Ritterbusch, D., Argillier, C., Białokoz, W., Blabolil, P., Breine, J., Jaarsma, N.G., Krause, T., Kubečka, J., Lauridsen, T.L., Nõges, P., Peirson, G., Virbickas, T., 2017. Response of fish communities to multiple pressures: development of a total anthropogenic pressure intensity index. Sci. Total Environ. 586, 502–511. https://doi.org/10.1016/j.scitotenv.2017.01.211.

Pool, S., Seibert, J., 2021. Gauging ungauged catchments – active learning for the timing of point discharge observations in combination with continuous water level measurements. J. Hydrol. 598, 126448. https://doi.org/10.1016/j.jhydrol.2021.126448.

Ramatlapeng, G.J., Atekwana, E.A., Molwalefhe, L., 2023. Spatial and temporal controls on the solute behavior of rivers in arid watersheds: the Okavango River, NW Botswana. J. Hydrol. 618, 129141. https://doi.org/10.1016/j.jhydrol.2023.129141.

Ramírez, C.A., Carvajal, Y., Bocanegra, R.A., Sandoval, M.C., 2018. Determination of the water level – discharge relationship in a river: simple or complex? Ing. Compet. 20, 45. https://doi.org/10.25100/iyc.v20i2.6354.

Richter, B.D., Baumgartner, J.V., Powell, J., Braun, D.P., 1996. A method for assessing hydrologic alteration within ecosystems. Conserv. Biol. 10, 1163–1174. https://doi.org/10.1046/j.1523-1739.1996.10041163.x.

Rinaldi, M., Surian, N., Comiti, F., Bussettini, M., 2013. A method for the assessment and analysis of the hydromorphological condition of Italian streams: the Morphological Quality Index (MQI). Geomorphology 180–181, 96–108. https://doi.org/10.1016/j.geomorph.2012.09.009.

Rinaldi, M., Belletti, B., Comiti, F., Nardi, L., Bussettini, M., Mao, L., Gurnell, A.M., 2015a. The Geomorphic Units survey and classification System (GUS). In: Deliverable 6.2, Part 4, of REFORM (REstoring rivers FOR effective catchment Management). European Commission, Brussels, pp. 33–47.

Rinaldi, M., Gurnell, A.M., Belletti, B., Berga Cano, M.I., Bizzi, S., Bussettini, M., Gonzalez del Tanago, M., Grabowski, R., Habersack, H., Klösch, M., Magdaleno Mas, F., Mosselman, E., Velasco, M.T., Vezza, P., 2015b. Final report on methods, models, tools to assess the hydromorphology of rivers. In: Deliverable 6.2, Part 1, of REFORM (REstoring rivers FOR effective catch-ment Management). European Commission, Brussels, pp. 67–70.

Rinaldi, M., Belletti, B., Bussettini, M., Comiti, F., Golfieri, B., Lastoria, B., Marchese, E., Nardi, L., Surian, N., 2017. New tools for the hydromorphological assessment and monitoring of European streams. J. Environ. Manag. 202, 363–378. https://doi.org/10.1016/j.jenvman.2016.11.036.

Rivers of Europe, 2022. Elsevier. https://doi.org/10.1016/C2017-0-03745-X.

Rusnák, M., Sládek, J., Kidová, A., Lehotský, M., 2018. Template for high-resolution river landscape mapping using UAV technology. Measurement 115, 139–151. https://doi.org/10.1016/j.measurement.2017.10.023.

Sály, P., Erős, T., Takács, P., Specziár, A., Kiss, I., Bíró, P., 2009. Assemblage level monitoring of stream fishes: the relative efficiency of single-pass vs. double-pass electrofishing. Fish. Res. 99, 226–233. https://doi.org/10.1016/j.fishres.2009.06.010.

Sankey, T., Donager, J., McVay, J., Sankey, J.B., 2017. UAV lidar and hyperspectral fusion for forest monitoring in the southwestern USA. Remote Sens. Environ. 195, 30–43. https://doi.org/10.1016/j.rse.2017.04.007.

Šarauskienė, D., Adžgauskas, G., Kriaučiūnienė, J., Jakimavičius, D., 2021. Analysis of hydrologic regime changes caused by small hydropower plants in lowland rivers. Water 13, 1961. https://doi.org/10.3390/w13141961.

Schmidt-Kloiber, A., Hering, D., 2015. www.freshwaterecology.info – an online tool that unifies, standardises and codifies more than 20,000 European freshwater organisms and their ecological preferences. Ecol. Indic. 53, 271–282. https://doi.org/10.1016/j.ecolind.2015.02.007.

Shiji, C., Dhakal, S., Ou, C., 2021. Greening small hydropower: a brief review. Energ. Strat. Rev. 36, 100676. https://doi.org/10.1016/j.esr.2021.100676.

Sun, M., Huang, K., Shao, J., Wu, W., Liang, X., 2022. Effects of mountain rivers cascade hydropower stations on water ecosystems. Restor. Ecol. 4, 17–26. https://doi.org/10.30564/re.v4i1.4259.

Sun, J., Du, W., Lucas, M.C., Ding, C., Chen, J., Tao, J., He, D., 2023. River fragmentation and barrier impacts on fishes have been greatly underestimated in the upper Mekong River. J. Environ. Manag. 327, 116817. https://doi.org/10.1016/j.jenvman.2022.116817.

Suska, K., Parasiewicz, P., 2020. Application of the mesohabitat simulation system (MesoHABSIM) for assessing impact of river maintenance and restoration measures. Water 12, 3356. https://doi.org/10.3390/w12123356.

Tharme, R.E., 2003. A global perspective on environmental flow assessment: emerging trends in the development and application of environmental flow methodologies for rivers. River Res. Appl. 19, 397–441. https://doi.org/10.1002/rra.736.

Timpe, K., Kaplan, D., 2017. The changing hydrology of a dammed Amazon. Sci. Adv. 3, e1700611 https://doi.org/10.1126/sciadv.1700611.

Tymków, P., Jóźków, G., Walicka, A., Karpina, M., Borkowski, A., 2019. Identification of water body extent based on remote sensing data collected with unmanned aerial vehicle. Water 11, 338. https://doi.org/10.3390/w11020338.

Van Treeck, R., Radinger, J., Noble, R.A.A., Geiger, F., Wolter, C., 2021. The European Fish Hazard Index – an assessment tool for screening hazard of hydropower plants for fish. Sustain. Energy Technol. Assess. 43, 100903. https://doi.org/10.1016/j.seta.2020.100903.

Van Treeck, R., Wolter, C., Cowx, I.G., Noble, R.A.A., King, M., van Zyll de Jong, M., Radinger, J., 2022. Risk assessment and decision making on mitigation measures. In: Rutschmann, P., Kampa, E., Wolter, C., Albayrak, I., David, L., Stoltz, U., Schletterer, M. (Eds.), Novel Developments for Sustainable Hydropower. Springer Nature, Cham, pp. 167–215. https://doi.org/10.1007/978-3-030-99138-8_15.

VanDusen, B.M., Theuerkauf, E.J., Fegley, S.R., Rodriguez, A.B., 2016. Monitoring overwash using water-level loggers resolves frequent inundation and run-up events. Geomorphology 254, 32–40. https://doi.org/10.1016/j.geomorph.2015.11.010.

Vassoney, E., Mochet, A.M., 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, 640. https://doi.org/10.3390/w11040640.

Vezza, P., Parasiewicz, P., Calles, O., Spairani, M., Comoglio, C., 2014. Modelling habitat requirements of bullhead (*Cottus gobio*) in Alpine streams. Aquat. Sci. 76, 1–15. https://doi.org/10.1007/s00027-013-0306-7.

Vezza, P., Ghia, D., Fea, G., 2016. Quantitative habitat models for the conservation of the endangered European crayfish *Austropotamobius pallipes* complex (Astacoidea: Astacidae). In: Kawai, T., Cumberlidge, N. (Eds.), A Global Overview of the Conservation of Freshwater Decapod Crustaceans. Springer International Publishing, Cham, pp. 339–358. https://doi.org/10.1007/978-3-319-42527-6_12.

Vezza, P., Zanin, A., Parasiewicz, P., 2017. Manuale tecnico-operativo per la modellazione e la valutazione dell'integrità dell'habitat fluviale. In: ISPRA – Manuali e Linee Guida 154/2017. ISPRA, Rome, Italy.

Virbickas, T., Vezza, P., Kriaučiūnienė, J., Akstinas, V., Šarauskienė, D., Steponėnas, A., 2020. Impacts of low-head hydropower plants on cyprinid-dominated fish assemblages in Lithuanian rivers. Sci. Rep. 10, 21687. https://doi.org/10.1038/s41598-020-78701-8.

Wang, L., Infante, D., Lyons, J., Stewart, J., Cooper, A., 2011. Effects of dams in river networks on fish assemblages in non-impoundment sections of rivers in Michigan and Wisconsin, USA: effects of dams in river networks. River Res. Appl. 27, 473–487. https://doi.org/10.1002/rra.1356.

Wang, Y., Zhang, N., Wang, D., Wu, J., Zhang, X., 2018. Investigating the impacts of cascade hydropower development on the natural flow regime in the Yangtze River, China. Sci. Total Environ. 624, 1187–1194. https://doi.org/10.1016/j.scitotenv.2017.12.212.

Ward, J.V., Stanford, J.A., 1983. The serial discontinuity concept of lotic ecosystems. In: Bartell, S.M., Fontane, T.D. (Eds.), Dynamics of Lotic Ecosystems. Ann Arbor Science, Michigan, USA, pp. 29–42.

Woodget, A.S., Austrums, R., 2017. Subaerial gravel size measurement using topographic data derived from a UAV-SfM approach: subaerial gravel size measurement using topographic UAV-SfM data. Earth Surf. Process. Landf. 42, 1434–1443. https://doi.org/10.1002/esp.4139.

World Meteorological Organization, 2019. Guidance on Environmental Flows – Integrating E-flow Science With Fluvial Geomorphology to Maintain Ecosystem Services. World Meteorological Organization, Geneva, Switzerland.

Worrall, T.P., Dunbar, M.J., Extence, C.A., Laizé, C.L.R., Monk, W.A., Wood, P.J., 2014. The identification of hydrological indices for the characterization of macroinvertebrate community response to flow regime variability. Hydrol. Sci. J. 59, 645–658. https://doi.org/10.1080/02626667.2013.825722.

Xiao, X., Chen, X., Zhang, L., Lai, R., Liu, J., 2019. Impacts of small cascaded hydropower plants on river discharge in a basin in southern China. Hydrol. Process. 33, 1420–1433. https://doi.org/10.1002/hyp.13410.

Yang, B., Dou, M., Xia, R., Kuo, Y.-M., Li, G., Shen, L., 2020. Effects of hydrological alteration on fish population structure and habitat in river system: a case study in the mid-downstream of the Hanjiang River in China. Glob. Ecol. Conserv. 23, e01090 https://doi.org/10.1016/j.gecco.2020.e01090.

Yue, Z., Huang, W., Xiong, L., Wang, Z., Wang, X., Wang, Q., Shen, Q., 2021. A new strategy for environmental flow management by using the remote sensing method. J. Clean. Prod. 325, 129226. https://doi.org/10.1016/j.jclepro.2021.129226.

Zhou, X., Huang, X., Zhao, H., Ma, K., 2020. Development of a revised method for indicators of hydrologic alteration for analyzing the cumulative impacts of cascading reservoirs on flow regime. Hydrol. Earth Syst. Sci. 24, 4091–4107. https://doi.org/10.5194/hess-24-4091-2020.