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# Linking mesohabitat delineation and landscape metrics to assess the riverscape following multiple dam removals

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**ABSTRACT**

Assessing the riverscape following dam removal requires measurable indicators of physical habitats. We developed and applied a framework for in-stream physical habitat assessment at three reaches of a Nordic lowland river undergoing dam removal and rapids restoration. Flow velocity and water depth were measured with an Acoustic Doppler Current Profiler under comparable pre- and post-restoration discharge. Measurements were interpolated, and spatially contiguous, homogeneous hydraulic patches were delineated using hierarchical clustering. Deterministic patch classification characterised habitat composition, and nine landscape metrics, reflecting hydraulic heterogeneity, spatial connectedness, and diversity, served as proxies for habitat quality. The delineated patches accurately represented spatially explicit hydraulic conditions pre- and post-restoration, and landscape metrics revealed clear restoration effects: incorporating the restored rapids as additional mesohabitat increased values in 25 of the 27 metric–reach combinations, with hydraulic heterogeneity rising 25–47%, and relative richness increasing by +0.10 (one additional habitat class) in each reach. These results emphasise the impact of restoring hydraulically diverse habitats. This study advances restoration impact assessment by linking meso-scale habitat delineation with landscape metrics from a riverscape perspective. The framework is transferable to other river environments and flexible in using hydrodynamic model outputs or field data, offering a practical approach for restoration planning and evaluation.

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## 1. Introduction

Rivers face persistent threats from expanding hydropower demands, simplification of channel morphology, flow regulation, and fragmentation (Newson and Newson 2000; Grill et al. 2019; Reid et al. 2019). Consequently, riverine freshwater biodiversity is endangered through altered flow and thermal regimes, reduced connectivity between rivers and their floodplains, lowered aquatic productivity, and restricted access to spawning and nursery habitats (Allan and Castillo 2007; Reid et al. 2019). Anthropogenic pressures acting at the landscape scale interfere with the geomorphic processes that maintain the riverscape and its biota, often leaving habitats that are both degraded and less heterogeneous (Allan 2004). Although lakes, reservoirs, and rivers cover only 2.3% of the Earth's surface, freshwater ecosystems provide habitat for at least 9.5% of described animal species (Reid et al. 2019) and are among the most vulnerable systems to habitat and species loss (Tickner et al. 2020; Haase et al. 2023; Dudgeon and Strayer 2025).

Despite extensive documentation of threats to freshwater biodiversity, large-scale and coordinated action to halt these losses has long been insufficient (Reid et al. 2019; Albert et al. 2021). Reversing biodiversity decline, described as 'bending the curve', requires the integration of river restoration with ambitious conservation strategies (Tickner et al. 2020). River restoration is commonly defined as a set of measures designed to reduce or eliminate anthropogenic constraints on the development of natural biodiversity patterns (Nestler et al. 2010; Palmer and Ruhi 2019). Among restoration actions, dam removal has emerged as an efficient measure to re-establish natural flow and sediment regimes, improve longitudinal continuity, and enhance floodplain-river interactions, thereby fostering species

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recovery and ecosystem functioning (Bellmore et al. 2019; Reid et al. 2019). Measuring restoration success through biotic status is challenging due to recovery time lags, natural variability, and difficulties in observing mobile organisms. Because a primary purpose of river restoration is to secure suitable habitat, evaluating restoration measures in terms of physical habitat is both logical and more practical (Parasiewicz et al. 2013). Habitat assessments enable the prediction of habitat changes resulting from restoration actions and are therefore valuable tools for both the design and evaluation of restoration projects (Alfredsen et al. 2004; Parasiewicz et al. 2013; Richer et al. 2019). A critical link to achieving restoration goals is the objective assessment of measurable indicators such as habitat composition and proxies of habitat quality. Habitat composition describes the types and spatial proportions of habitat units within a reach, whereas habitat quality proxies reflect the structural and hydraulic conditions that underpin ecological suitability. Together, these perspectives provide a complementary framework for evaluating restoration outcomes (Woolsey et al. 2007; Wallis et al. 2012; Parasiewicz et al. 2013).

Rivers are nested hierarchical systems in which processes and forms at larger scales determine those at smaller scales (Allan and Castillo 2007; Belletti et al. 2017). The very complex and dynamic nature of rivers is particularly amenable to a landscape ecology perspective. Acknowledging that rivers form complex mosaics of habitat types and environmental gradients defined by high connectivity and spatial complexity, riverine landscapes are increasingly conceptualised as riverscapes (Fausch et al. 2002; Ward et al. 2002). This perspective is applicable across a broad range of scales, from braided rivers and their valleys (Tockner et al. 2002) to individual habitat patches (Palmer et al. 2000). Within this hierarchy, the meso-scale is of practical interest for river management, as many restoration measures directly affect habitats at this scale (Newson and Newson 2000; Wegscheider et al. 2020). Meso-scale habitat approaches have therefore been increasingly applied in river studies and are expected to gain further importance (Hauer et al. 2009; Tamminga and Eaton 2018; Wegscheider et al. 2020; van Rooijen et al. 2021). Mesoscale riverine features comprise geomorphic units spanning the channel width and smaller hydraulic units, reflecting heterogeneity within geomorphic units (Wyrick et al. 2014; Belletti et al. 2017). Hydraulic units, also referred to as hydraulic patches, have been defined as two-dimensional, discharge-dependent, contiguous areas that are homogeneous compared to, and significantly distinct from, their surroundings (Dunbar et al. 2012; van Rooijen et al. 2021). Numerous approaches exist to assess physical habitats, ranging from field surveys and aerial imagery to numerical hydrodynamic modelling (Legleiter and Goodchild 2005; Wyrick et al. 2014; Tamminga and Eaton 2018; Farò et al. 2022, 2025).

Landscape metrics are well established in terrestrial ecology, but their application in aquatic systems remains limited (Woolsey et al. 2007; Wallis et al. 2012; Weber et al. 2025), despite the riverscape perspective providing a clear conceptual basis for their use in rivers. Rooted in quantitative landscape ecology, which links spatial patterns of physical habitat to ecological processes (Turner and Gardner 2015), landscape metrics quantify the configuration and composition of habitat mosaics and can serve as proxies for habitat quality from complementary conceptual perspectives. Three thematic groups are particularly relevant in riverine settings: hydraulic heterogeneity, which captures spatial variability in flow velocity and water depth and thereby the range of hydraulic conditions available to biota (Gostner et al. 2013); spatial connectedness, which describes the size, shape, and contiguity of habitat patches and reflects fragmentation of the habitat mosaic (McGarigal and Marks 1995); and diversity, which characterises compositional richness and evenness across habitat classes and is grounded in classical biodiversity theory (Magurran 2004). Previous studies have used such metrics to describe the spatial and temporal configuration of hydraulic patches (Wallis et al. 2012), evaluate river restoration outcomes (Woolsey et al. 2007), and quantify habitat complexity in restored streams (Weber et al. 2025).

In this study, we delineate hydraulic patches using hierarchical clustering to characterize meso-scale habitat composition and link it with landscape metrics for evaluating habitat quality proxies following multiple dam removals in a Nordic lowland river. The study was conducted in the Hiitolanjoki River, which originates in south-eastern Finland and flows into Lake Ladoga, Russia. The dam removals on the Finnish side of the river represent major restoration, fish migration, and ecological rehabilitation efforts in Northern Europe and have received national and international recognition (Dam Removal Award 2022; BBC 2024; Regional Council of South Karelia 2024). Assessing the outcomes of such large-scale restoration efforts requires detailed characterisation of the resulting hydraulic conditions, yet most existing field methods for measuring riverine hydraulics are slow and laborious (Rhoads et al. 2003). Acoustic Doppler Current Profilers (ADCPs) enable rapid mapping of three-dimensional flow velocity, together with water depth *via* its vertical echo sounder beam, at scales appropriate for mesohabitat simulation (Shields and Rigby 2005). ADCPs use acoustic pulses measuring a range of hydraulic variables, such as flow velocity at different depths through most of the water column, discharge rates from transects, and underwater topography (Mueller et al. 2013). We delineated hydraulic patches based on interpolated hydraulic field data derived from ADCP measurements of flow velocity and water depth. The patch delineation builds on unsupervised hierarchical clustering with a spatial contiguity constraint (van Rooijen et al. 2021) but is applied here for the first time in a non-wadable Nordic lowland river based on field measurements rather than hydrodynamic model outputs.

The delineated and classified mesohabitats are the basis for assessing habitat composition and quantifying habitat quality proxies using ecologically relevant landscape metrics. By linking mesohabitats with landscape metrics, restoration impacts on downstream mesohabitats can be identified, and the influence of restored rapids as additional mesohabitat on overall physical habitat conditions can be evaluated. The objective assessment of habitat composition and habitat quality proxies supports restoration planning, outcome evaluation, and conservation strategies aimed at creating conditions conducive to reversing freshwater biodiversity loss (Woolsey et al. 2007; Palmer and Ruhi 2019; Weber et al. 2025). Accordingly, this study addresses the following research aims:

1. To assess habitat composition by delineating and classifying hydraulic patches from field data collected before and after dam removal under reach-wise comparable discharge conditions.
2. To quantify habitat quality proxies of downstream mesohabitats following dam removal and river restoration using landscape metrics.
3. To evaluate the influence of restored rapids as additional mesohabitat on overall habitat quality proxies.

The paper concludes by discussing the framework's strengths and limitations and by identifying avenues for future research.

## 2. Study site

The study site is located along the Hiitolanjoki River in south-eastern Finland (Figure 1), within the Southern Boreal climate zone, characterised by cold, snowy winters and relatively warm summers (Peel et al. 2007). The river flows from Kivijärvi Lake to Lake Ladoga in Russia, with a mean discharge of 11 $m^3/s$ and peak flows driven by spring snowmelt (Schlobies et al. 2025). Hiitolanjoki River is home to Finland's last naturally reproducing population of landlocked salmon (Salmo salar m. sebago) (Ozerov et al. 2010; Regional Council of South Karelia 2024), a critically endangered species whose upstream spawning habitat had been blocked for over a century by three consecutive hydropower dams constructed in the early twentieth century (Ozerov et al. 2010; Regional Council of South Karelia 2024). Between 2021 and 2023, all three dams were removed in downstream-to-upstream sequence: Kangaskoski (autumn 2021), Lahnasenkoski (autumn 2022), and Ritakoski (autumn 2023), eliminating a combined vertical drop of 18 metres and fully restoring longitudinal continuity (Regional Council of South Karelia 2024). Previously, these dams produced 1.8 MW of hydropower (Iho et al. 2023), and their removals were driven by maintenance and environmental costs outweighing economic benefits. An equally important motivation was to restore riverine habitats and enhance migration for endangered migratory fish (BBC 2024; Regional Council of South Karelia 2024). At each former dam site, rapids with coarse substrate of boulders and cobbles were reconstructed to overcome the drop height, and a submerged boulder sill functioning as a grade control structure is situated at the rapids upstream head to maintain upstream water surface elevations at approximately pre-removal levels.

Our study comprises three reaches situated downstream of each respective dam removal site and less than 5 km apart: Ritakoski (Reach A), Lahnasenkoski (Reach B), and Kangaskoski (Reach C). The reaches range from approximately 150 to 450 m in length, 25 to 65 m in width, and 3.1 to 5.5 m in maximum water depth at the discharge conditions listed in Table S1 encountered during the field campaigns. The bed substrate is dominated by fine sand and silt, supporting submerged vascular macrophytes, and the banks are bordered by mature riparian forest. The restored rapids create novel mesohabitat, enable local adjustment of flow paths, and promote upstream migration of aquatic species.

The Finnish Environment Institute (Syke) provides daily discharge information from the former gauging station at Kangaskoski. In Figure 2, we provide a hydrological characterization of Hiitolanjoki River based on a long-term discharge time series at Kangaskoski gauge station and a subsequent flow duration curve, where the 5th and 95th percentiles were calculated to characterise the prevailing low- and high-flow conditions. The incomplete years 2005, 2010, 2016, 2017, and 2018 were excluded from the discharge duration curve. The hydroacoustic measurements analysed in this study were either collected under high or low discharge conditions. The low-flow survey with prevailing discharge of 3.3 $m^3/s$, exceeded 97.3% of the time, while the high-flow survey corresponds to 19.5 $m^3/s$, exceeded 2.2% of the time (Figure 2). Given that no relevant tributaries exist

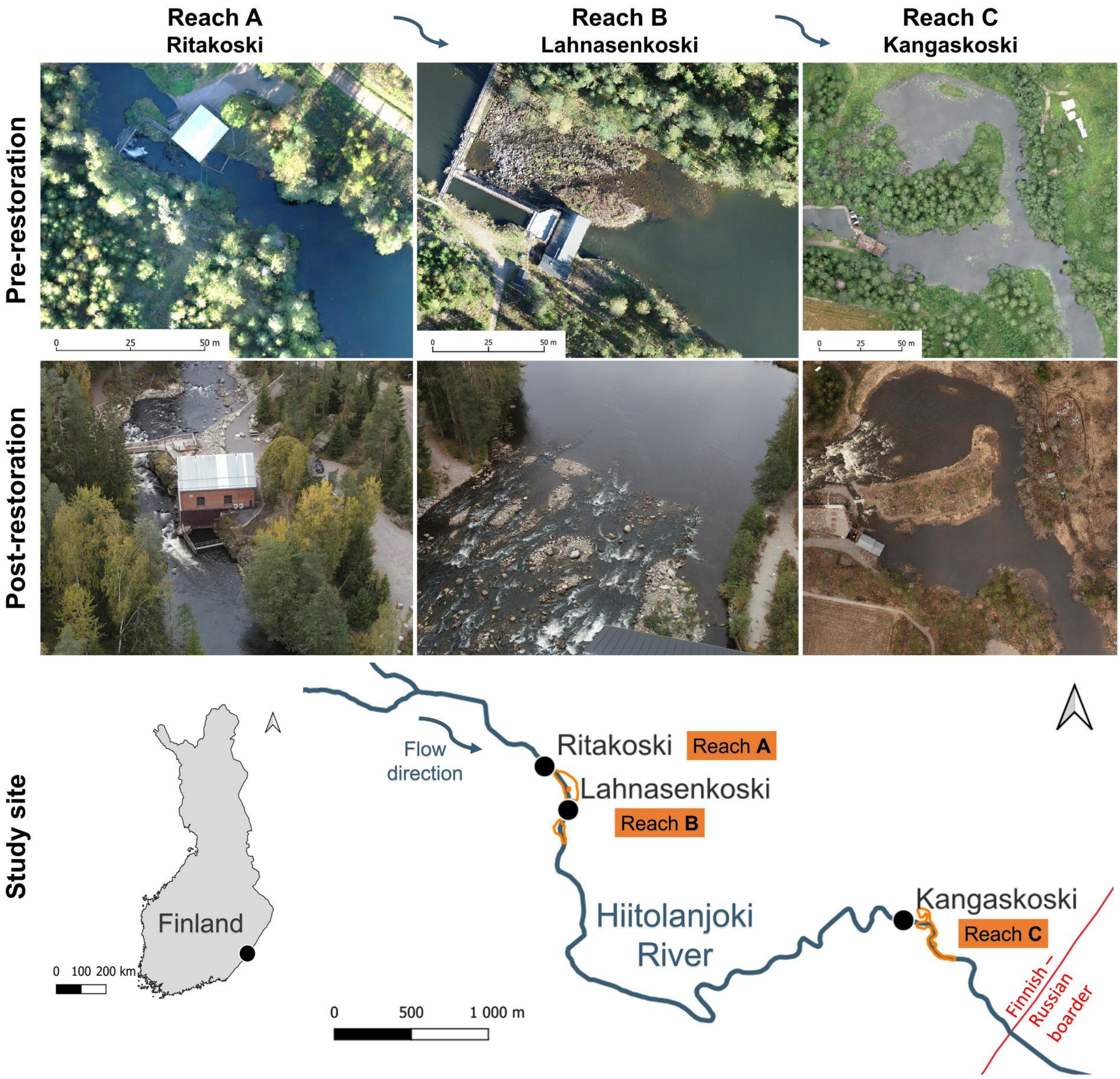


Figure 1. Pre- and post-restoration images of the study Reaches A–C and their locations at Hiitolanjoki River (Finland). Mesohabitats are delineated for the extents of Reach A, B and C downstream of their former dams at Ritakoski, Lahnasenkoski and Kangaskoski.

between the three study reaches and their spatial extent spans less than 5 km, a single flow duration curve was considered applicable to all reaches.

## 3. Materials and methods

The framework of the meso-scale habitat assessment and applied methodology is composed of several steps (Figure 3), described in detail in the following subsections.

### *3.1. Hydroacoustic field data collection*

To obtain non-intrusive, three-dimensional velocity measurements and water depth from the study reaches, we employed a SonTek HydroSurveyor-M9 in all field surveys except for October 2025 when we applied a Teledyne RDI RiverPro 1200 ADCP. For surveys in May and September 2021, the SonTek HydroSurveyor-M9 was mounted on a kayak and operated with a SonTek DGPS atop the M9 unit. For field campaigns in May 2022 the SonTek HydroSurveyor-M9 unit was deployed on a motorized floating platform and paired with a North SmaRTK GNSS receiver and the RTK-GNSS base station set up onshore. In October 2025 the Teledyne RDI RiverPro 1200 was used in combination with a GNSS pair of Hemisphere S631, and a Subtop ADCP keeper used as a motorized platform. Both the SonTek HydroSurveyor-M9 and Teledyne RDI RiverPro 1200 house nine beams and velocity measurements are accurate to ± 0.2 cm/s (SonTek 2013; Teledyne Marine 2024). The instruments differ in their minimum water depth for velocity profiling, with the SonTek M9 capable of profiling from 0.06 m and the Teledyne RiverPro from 0.12 m

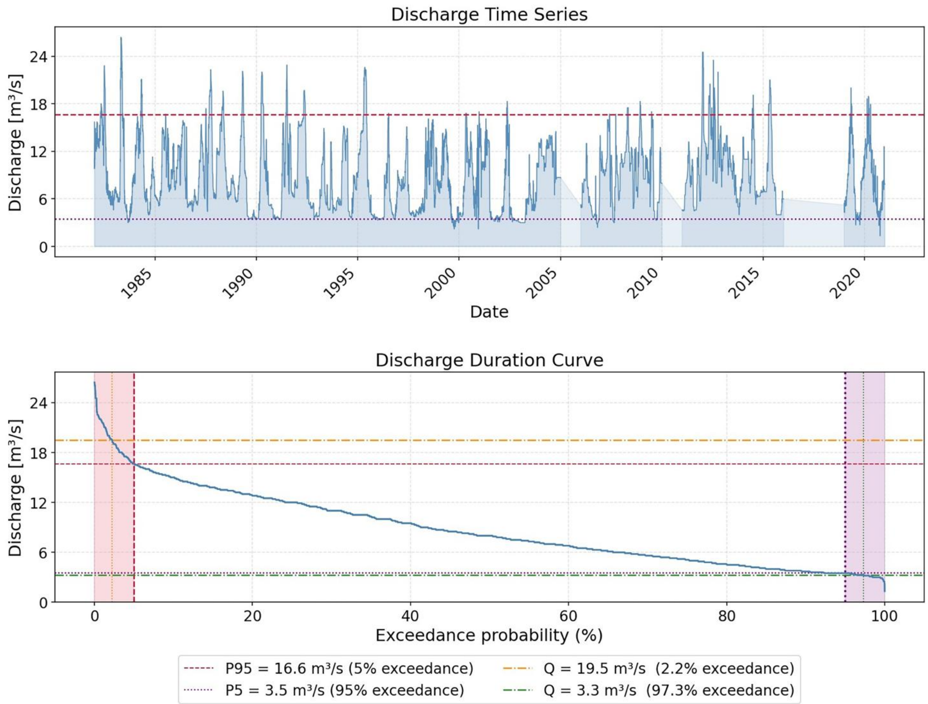


**Figure 2.** Long-term discharge time series and discharge duration curve from Kangaskoski gauging station at Hiitolanjoki River from 1982 to 2020. For Reach A and B discharges were 3.3 m$^3$/s (September 2021, pre-dam removal) and 3.2 m$^3$/s (October 2025, post-dam removal), and for Reach C discharges were 19.6 m$^3$/s (May 2021, pre-dam removal) and 19.5 m$^3$/s (May 2022, post-dam removal), respectively (Table S1).

depth below the transducer. The transducer depth below the water surface was 0.06 m when the SonTek unit was mounted on a kayak (September 2021) and 0.08 m for all other surveys using a motorized floating platform, resulting in minimum measurable water depths ranging from approximately 0.12 m to 0.20 m depending on the instrument and deployment configuration. To ensure comparability across measurement campaigns, only congruent water areas where valid measurements were obtained during both pre- and post-restoration surveys were used for subsequent analysis (cf. 3.2).

Discharge was acquired with an ADCP by conducting 4–6 repeat transects from the Kangaskoski site, averaging the individual transect discharge rates as reported in Table S1. At Reaches A and B, the collected ADCP measurements for the most comparable discharge rates for both, pre- and post-restoration occurred under autumn low-flow (pre-restoration: September 2021; post-restoration: October 2025; $Q = 3.3$ and 3.2 m$^3$/s, respectively). At Reach C, the spring high-flow measurements were the most similar pre- and post-restoration discharges (pre-restoration: May 2021; post-restoration: May 2022; $Q = 19.6$ and 19.5 m$^3$/s, respectively) (Table S1; Figure 3, step 1). The area-wide ADCP surveys at Reach C coincided with the discharge measurement dates listed in Table S1, while for both, Reaches A and B, surveys were conducted with a one-day offset on 23.09.2021 and 03.10.2025. In May and September 2021 as well as May 2022 Ritakoski and Lahnasenkoski hydropower plants at Reaches A and B were still operating, while the lowermost Kangaskoski dam at Reach C was already demolished in autumn 2021 (Table S1).

Throughout this paper, 'flow velocity' based on the collected field data refers to depth-averaged flow velocity, which integrates the velocity profile over the entire measurable water column. For better readability, we use 'flow velocity' exclusively hereafter to denote the depth-averaged velocity unless otherwise specified.

To remove spikes in the hydroacoustic data, each flow velocity measurement was compared to the median of a rolling window containing nine consecutive ADCP ensemble values with the analysed value in the centre. If a central flow velocity measurement differed by more than ±150% from the median of its rolling window, it was excluded from subsequent analysis. Unreliable hydroacoustic measurements, e.g. affected by aquatic vegetation which obstructs or scatters the acoustic signals of the ADCP, were further removed from the dataset.

To account for the varying ADCP data sampling per field campaign we only included measurements within a pre-defined Area of Interest (AOI) for the subsequent mesohabitat delineation (Figure 3, step 2). Hereby, we created 2-m-buffers around the pre- and post-restoration ADCP measurements and unified them to form polygons of their overlap area. We then derived a concave hull with ratio = 0.15 from the exterior overlap area for generating a tight boundary. We clipped the concave hull with a polygon solely covering river area, effectively creating a

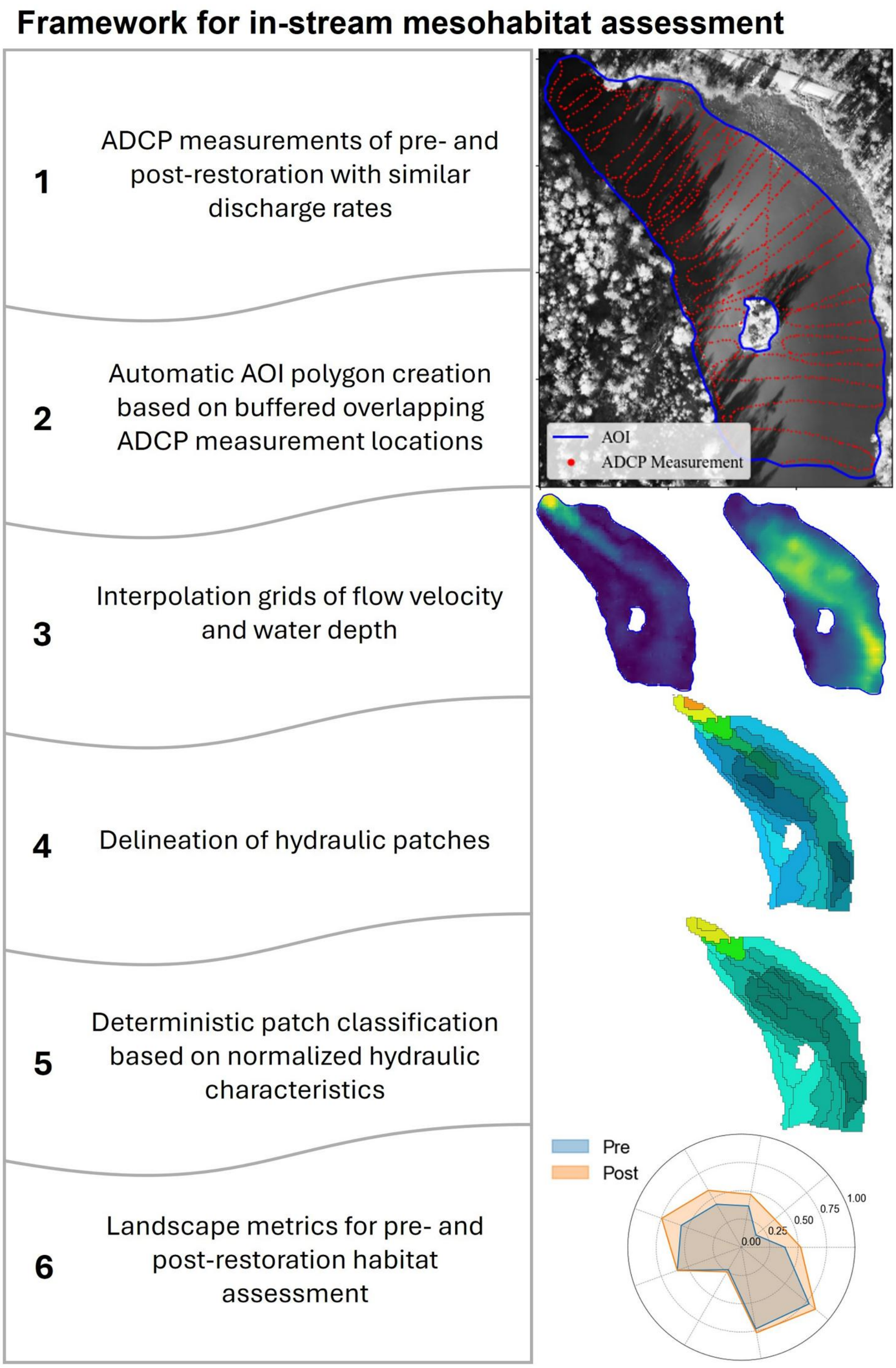


**Figure 3.** Framework of the in-stream mesohabitat assessment following dam removal and river restoration.

reach-wise AOI polygon defining the spatial extent for the following interpolation step (cf. 3.2). The AOI ensures that areas farther than 2 m away from pre-and-post-restoration ADCP measurements and land areas are neglected.

### *3.2. Processing of field-based flow velocity and water depth*

The pre-processed ADCP measurement points were used for calculating relevant statistical metrics to describe the pre- and post-restoration flow velocity and water depth of the studied sites. Hereby, the point measurements were spatially aggregated using an empty $2 \times 2$ m regular grid within the AOI polygon, which is in a next step also used for interpolation. For the statistical analysis we identified grid cells containing one or more ADCP measurements. For grid cells containing multiple measurements, flow velocity and water depth values were averaged cell-wise. Furthermore, for calculating the statistics, only grid cells with measurements from both pre- and post-restoration periods were included to enable direct spatial comparison in the subsequent kernel density estimation plots. We conducted Inverse Distance Weighting (IDW) interpolation per pre-and post-restoration date based on the extent of the $2 \times 2$ m grid used for the statistical analysis (Figure 3, step 3). The interpolation grid resolution of $2 \times 2$ m was selected to reflect the spacing between adjacent survey tracks, which, rather than the finer along-track ensemble spacing, limits the effective resolution recoverable across the channel. The same resolution was applied consistently for both pre- and post-restoration datasets to ensure comparability. For the interpolation we now included all pre-processed ADCP measurements, which were cell-wise aggregated by their means to counteract locally denser point measurement sampling. IDW calculates estimated cell values as a weighted average of values from neighbouring known cells. The weighting is inversely related to distance with closer cells having more influence. We selected $k = 20$ neighbours, which determines the number of known cells for each estimate and $p = 1$ as the power parameter reflecting how strongly distance influences weighting. Flow velocities are computed in a final step from the individually interpolated velocity components u and v. By calculating the flow velocity based on the interpolated u and v components we preserved the vector properties of velocity and ensured accurate physical representation of the flow field (Tsubaki et al. 2012).

To define the spatial extent of the rapids mesohabitat included for calculating habitat quality proxies (cf. 4.2), we digitised the common wetted channel area pre- and post-restoration based on orthomosaics where the rapids were constructed. We excluded the areas of the former spillways which are nowadays part of the restored rapids but were characterized by frequently changing hydraulic conditions while the hydropower plants were still operating. Then we converted the digitised polygons into grids of $2 \times 2$ m to match the spatial resolution of the AOIs grids of the study reaches.

To characterise pre-restoration hydraulic conditions in the channel areas later occupied by the rapids, we IDW-interpolated ADCP measurements onto a $2 \times 2$ m grid and based on cell-wise mean aggregation computed the mean flow velocity and water depth from cells containing $\geq 1$ ADCP measurement.

After restoration, the rapids were not possible to survey by ADCP due to the very shallow water depths and very fast current flow. To allow an approximation of the rapids as additional habitat, we generalized their hydraulic conditions based on flow measurements with an Acoustic Doppler Velocimeter (ADV: SonTek Flowtracker2), depth measurements with RTK-GNSS Trimble R12i Rover, and large-scale particle image velocimetry (LSPIV) from Schlobies et al. (2025). For the Lahnasenkoski rapids (Reach B), 15 measurements of near-surface flow velocity and water depth were collected on 3 October 2025 using an ADV. Measurements yielded a mean flow velocity of 0.45 m/s and a mean water depth of 0.38 m. However, due to safety constraints and the likely presence of salmon spawning redds, sampling was restricted to near-bank positions, characterized by lower current flow within the cross-section. The full rapids are expected to exhibit higher velocities and greater depths. Accordingly, a mean flow velocity of 0.5 m/s and water depth of 0.5 m were adopted as conservative, field-based approximations for the rapids.

For the Ritakoski rapids (Reach A), no independent field measurements were available. Given that discharge conditions and water surface slopes were similar to Reach B, the same approximated values of 0.5 m/s and 0.5 m were applied for Reach A.

To characterize hydraulic conditions in the Kangaskoski rapids at Reach C, we combined drone-derived surface flow velocities with GNSS-based bed elevation surveys. A LSPIV analysis of drone-borne videos recorded on 4 May 2022 yielded a mean surface flow velocity of 1.34 m/s within the rapids (Schlobies et al. 2025). Given the near-uniform velocity profiles typical of shallow, rough-bedded rapids, this value serves as a solid approximation of the depth-averaged flow velocity. The rapids were surveyed on 4 September 2025 using a Trimble R12i GNSS rover. Combining 1,485 bed elevation measurements within the rapids with the water surface elevations along the rapids determined for 4 May 2022, we calculated a mean water depth of 0.65 m. The mean flow velocity and mean water depth used to assess the impact of the rapids on overall habitat quality proxies are listed in Table S2.

### *3.3. In-stream hydraulic patch delineation*

For the automatic delineation of in-stream hydraulic patches, we developed PatchBuilder (https://doi.org/10.5281/zenodo.18493040), a software-agnostic Python reimplementation of the BASEmeso algorithm originally built as a QGIS plugin (van Rooijen et al. 2021). Both tools use agglomerative hierarchical clustering with a spatial contiguity criterion to delineate patches based on contiguous patch homogeneity and patch boundary contrast.

PatchBuilder enables fast geospatial patch delineation based on irregular mesh or rectangular grid-cell polygons and associated numeric variables and is applicable across a range of fields and use cases. Here, PatchBuilder groups the equally weighted, gridded input variables flow velocity and water depth in patches based on how similar these are to each other (Figure 3, step 4). It is a bottom-up clustering, where initially all patches are singletons, i.e. patches consist of a single grid cell containing water depth and flow velocity information. At each iteration, similar patches are merged until all grid cells are part of one bigger root patch using a 4-neighbour rule. Like BASEmeso, PatchBuilder performs hierarchical clustering using Ward's method (Ward 1963), which considers both the Euclidean distance between patches in variable space and the distribution of variable values within each patch. We used the StandardScaler() function from the Python *sklearn.preprocessing* package (Pedregosa et al. 2011) to standardize the water depth and flow velocities using z-scores, to ensure that the two independent variables contribute equally to the clustering process regardless of their original scales and units.

PatchBuilder requires the final number of patches ($n$) to be defined, whereas the chosen number should reflect an estimate of the actual number of patches present within the river reach. However, in practical applications, this number is typically not known in advance. The authors tested varying numbers of patches on the study reaches and validated afterward by comparing different choices of $n$ in relation to the spatial configuration and shape of the delineated pre- and post-restoration patches. The resulting patch delineations for $n = 10–100$ from Reach A in Figure S3, and the corresponding landscape metrics values, calculated from the classified patches of each study reach, are presented in Figure S4. We decided on 25 patches for both pre- and post-restoration at Reaches A and B aiming for a suitable patch number representing the hydraulic conditions of the study reaches. At Reach C we considered a patch number of 50 patches for both pre- and post-restoration due to the more complex, meandering reach structure and the presence of a side channel.

### 3.4. Classification of in-stream hydraulic patches

Hydraulic patches delineated with PatchBuilder (cf. 3.3) may differ spatially while representing overarching habitat conditions. We therefore applied a deterministic, rule-based classification based on mean flow velocity and mean water depth of the delineated mesohabitats within each of the downstream AOIs separately (Figure 3, step 5). Patch-wise means per study reach were normalized to [0,1] to define a reach-specific, dimensionless feature space, which was subdivided into nine hydraulic habitat classes (*slow/moderate/fast* × *shallow/intermediate/deep*; Figure 4). For visualization (cf. 4.1), individual patches were first coloured using a continuous HSV gradient spanning the full normalized feature space. In a second step, patches were deterministically assigned to one of the nine classes and coloured using the canonical HSV colour corresponding to the centre of each class region, enabling consistent, interpretable, and spatially explicit visualization of hydraulic habitat structure (cf. 4.1).

The pre-restoration habitat classes for the three channel areas before the rapids were constructed (Table S2) were assigned based on the absolute class boundaries of patch-wise means of flow velocity and water depth per study reach (Figure 4), using the means of flow velocity and water depth measured by ADCP from the pre-rapids channel areas.

For classifying the novel rapids mesohabitat, an additional post-restoration habitat class *very fast* × *very* shallow was assigned to each of the three restored rapids (Table S2) to account for the very distinct hydraulic conditions in comparison to the delineated and classified mesohabitats of each of the three study reaches downstream of the rapids.

### 3.5. Landscape metrics as proxies for in-stream habitat quality

Inspired by principles of quantitative landscape ecology, which link spatial patterns of physical habitat to ecological processes (Turner and Gardner 2015), we selected nine landscape metrics to assess the effects of dam removal and river restoration on class-based mesohabitats (cf. 3.4; Figure 3, step 6). The selected metrics listed in Table 1 serve as proxies for habitat quality from different conceptual perspectives and are subdivided into three thematic subgroups: hydraulic heterogeneity, spatial connectedness and diversity. Their interpretation follows established concepts in river and landscape ecology (McGarigal and Marks 1995; Jaeger 2000; Gostner et al. 2013), with diversity and evenness grounded in classical biodiversity theory (Shannon 1948; Pielou 1966; Magurran 2004), describing habitat complexity and balance, which are key proxies for ecological integrity (Woolsey et al. 2007).

Hydraulic heterogeneity expressed by the HMID (Gostner et al. 2013) captures spatial variability in flow velocity and water depth per patch, with higher values indicating more diverse hydraulic conditions that may support a wider range of aquatic habitats. Flow velocity heterogeneity and water depth heterogeneity, expressed through coefficients of variation (CV), strongly influence habitat suitability and are also considered in Woolsey et al. (2007) for river restoration outcomes. Additionally, these indicate whether the flow velocity or the water depth is the more relevant hydraulic variable affecting the HMID

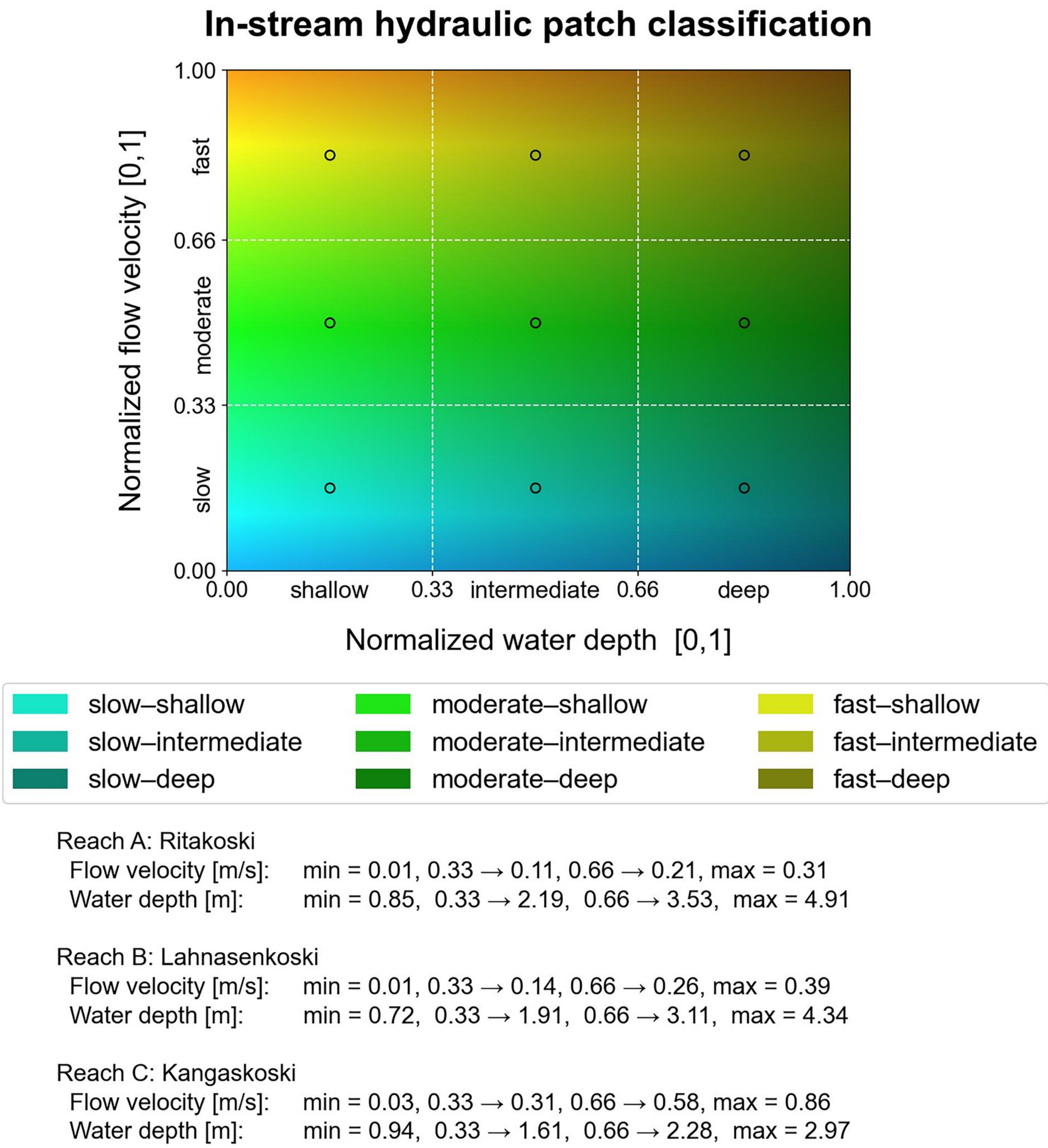


**Figure 4.** Bivariate colour legend for mapping the normalized patch-wise means of flow velocity and water depth per reach onto a continuous hue–brightness gradient. The full HSV spectrum is used to colour individual hydraulic patches based on their normalized values. For categorical interpretation, patches are deterministically grouped into nine hydraulic habitat classes defined by the cross-combination of flow velocity (slow, moderate, fast) and water depth (shallow, intermediate, deep) and are coloured using the canonical HSV colour at the centre of each class. The reach-specific normalization can result in empty classes and multiple patches assigned to the same class. The absolute class boundaries of the patch-wise means of flow velocity and water depth per study reach are stated for Reach A, B and C separately.

when comparing pre- and post-restoration conditions.

Coherence (Jaeger 2000) expresses the probability that two randomly selected cells lie within the same habitat patch; it is derived from the patch-size distribution and is the complement of landscape division. Higher values indicate a landscape dominated by fewer, larger patches, i.e. a less subdivided, less fragmented habitat mosaic.

Area-per-perimeter characterizes habitat shape compactness, with higher values indicating more compact patches and reduced edge influence. Here, we use the area-weighted mean area-per-perimeter to ensure that larger habitat patches have a proportionally greater influence on the compactness metric than small patches. Mean patch size provides an indicator of habitat connectedness, where larger average patch sizes imply spatially more extensive and thus less fragmented habitat units. We applied 4-sided connectivity to determine adjacent pixels aiming for compactness when calculating coherence, area-per-perimeter and mean patch size.

**Table 1.** Landscape metrics subdivided into hydraulic heterogeneity, structural connectedness, and diversity.

| | Metric | Symbol | Mathematical definition |
|---|---|---|---|
| Hydraulic heterogeneity | Flow velocity heterogeneity (Gostner et al. 2013) | CV_v | CV_v = σ_v / μ_vwhere μ_v and σ_v are the mean and standard deviation of flow velocity per patch, respectively. |
| | Water depth heterogeneity (Gostner et al. 2013) | CV_d | CV_d = σ_d / μ_d where μ_d and σ_d are the mean and standard deviation of water depth per patch, respectively. |
| | Hydraulic heterogeneity (Gostner et al. 2013) | HMID | HMID = √ (CV_d$^2$ + CV_v$^2$)where CV_d and CV_v are the coefficients of variation of water depth and flow velocity per patch, respectively. |
| Structural connectedness | Area-per-perimeter (McGarigal and Marks 1995) | A/P | A/P = A_j / P_j where A_j is patch area and P_j its perimeter. |
| | Mean patch size (McGarigal and Marks 1995) | MPS | MPS = (1 / J) · Σ A_j where A_j is the area of patch j (in number of cells) and J is the total number of habitat patches. |
| | Coherence (Jaeger 2000) | C | C = (Σ A_j$^2$) / N$^2$ where A_j is the area of patch j (in number of cells) and N is the total number of habitat cells. |
| Diversity | Relative richness (McGarigal and Marks 1995) | R_rel | R_rel = S / S_max where S is the number of habitat classes present and S_max is the maximum number of possible habitat classes. |
| | Shannon's Diversity Index (Shannon 1948) | H′ | H′ = − Σ (p_k · ln p_k) where p_k is the proportion of habitat class k. |
| | Pielou's Evenness Index (Pielou 1966) | J′ | J′ = H′ / ln(S) where H′ is Shannon diversity and S is the number of habitat classes present. |

Shannon's Diversity Index and relative habitat richness describe compositional habitat diversity, with Shannon's Diversity Index integrating both the number of observed habitat classes and their proportional areal representation, and relative richness indicating the proportion of distinct habitat types present in relation to the total number of habitat classes. Pielou's Evenness Index complements these measures by indicating whether habitat area is evenly distributed among classes. Within the conceptual framework applied here, increasing metric values are interpreted as indicative of improved habitat quality proxies, reflecting a higher degree of habitat diversity, spatial connectedness, and hydraulic heterogeneity in the riverine environment.

To enable joint visualization we ensured a common [0,1] range by applying scaling functions chosen according to each metric's mathematical properties: the non-negative, unbounded metrics HMID, CV flow velocity, CV water depth, and area-per-perimeter were scaled using a monotonic ratio transform $x/(1+x)$; mean patch size was scaled using a habitat-area-dependent reference; Shannon's Diversity Index was normalized by its theoretical maximum of habitat classes; and the inherently bounded metrics Pielou's Evenness Index, coherence, and relative richness were left unchanged. The monotonic ratio transform used for the unbounded metrics is convenient because it maps [0, ∞] to [0, 1] and is anchored at zero, but it compresses differences at larger metric values more strongly than at smaller ones. Thus, scaling is used solely for joint visualization in the radar plots and all quantitative statements in this study refer to the raw, untransformed values.

In a first step we calculated the landscape metrics solely for the three AOIs downstream of the restored rapids. Hereby, we aim to evaluate the natural self-adjustment of the downstream mesohabitats following dam removals and rapids restoration. In a second step, we aim to approximate the impact of the restored rapids as additional mesohabitat on overall habitat quality proxies. We consider the three restored rapids as novel mesohabitat to add to the existing classified habitat mosaics at Reach A, B and C.

Additionally, a sensitivity analysis was performed by varying the post-restoration flow velocity and water depth of the rapids patch by ±20% relative to the baseline values provided in Table S2.

## 4. Results

### 4.1. Mesohabitat composition following dam removals and river restoration

Kernel density estimates of flow velocity and water depth (Figure 5) characterize the prevailing hydraulic conditions in Reach A, B and C for the survey dates. Additionally, hierarchical clustering using PatchBuilder (cf. 3.3) delineated 25 hydraulic patches in Reaches A and B and 50 patches in Reach C, coherently representing these underlying hydraulic conditions at the meso-scale.

In Reach A, water depth distributions shifted due to human-induced material backfilling associated with trail construction along the left bank (Figure 5, A2; Figure S5, A4), corresponding to a transition from slow–deep to slow–shallow conditions (Figure 6, A3–A4). Additional backfilling during restoration of the Lahnasenkoski rapids resulted in shallower water depths and locally increased flow velocities in the downstream section (Figure S5, A3; Figure 6, A2).

In Reach B, pre-restoration peak flow velocities occurred near the hydropower plant outlet (Figure

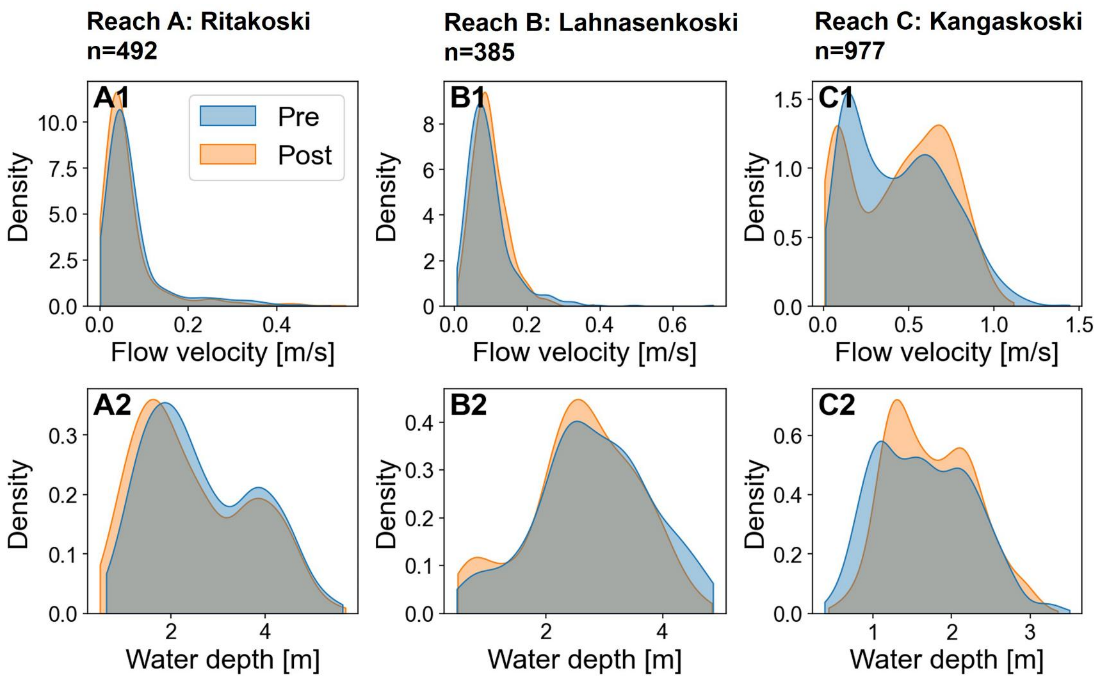


**Figure 5.** Kernel density estimates of averaged flow velocity and water depth for Reaches A–C based on common pre- and post-restoration grid cells. For Reach A and B discharges were 3.3 $m^3/s$ (September 2021) and 3.2 $m^3/s$ (October 2025), and for Reach C discharges were 19.6 $m^3/s$ (May 2021) and 19.5 $m^3/s$ (May 2022) (Table S1). The hydroacoustic measurements analysed in this study were collected under low-flow conditions for Reach A and B and under high-flow conditions for Reach C (Figure 2).

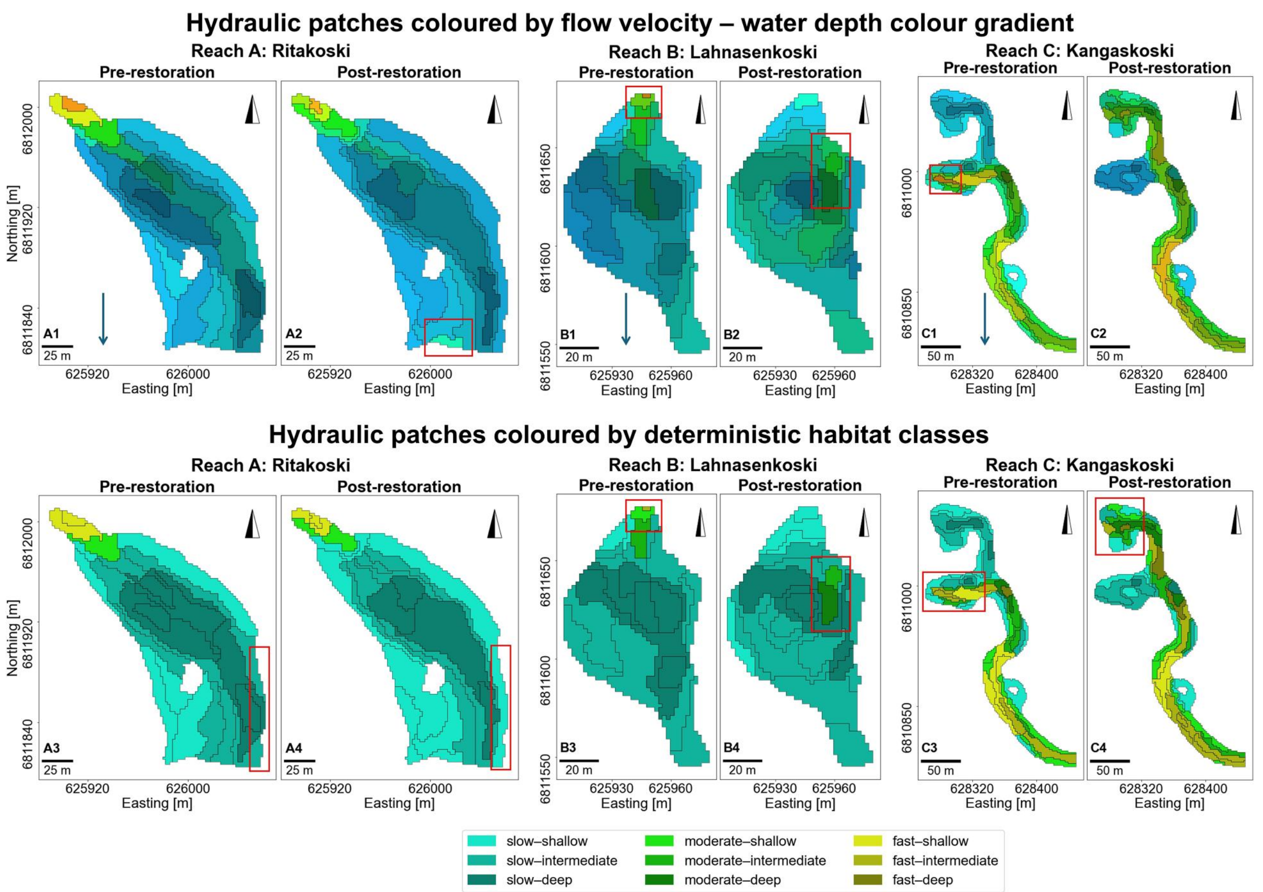


**Figure 6.** Pre- and post-restoration hydraulic patches for Reaches A–C. Patches A1–C2 are coloured by normalized mean flow velocity and water depth using the HSV palette (Figure 4). Patches A3–C4 are coloured by deterministic mesohabitat class. Arrows indicate flow direction. Red boxes indicate locations of special interest referred to in Results.

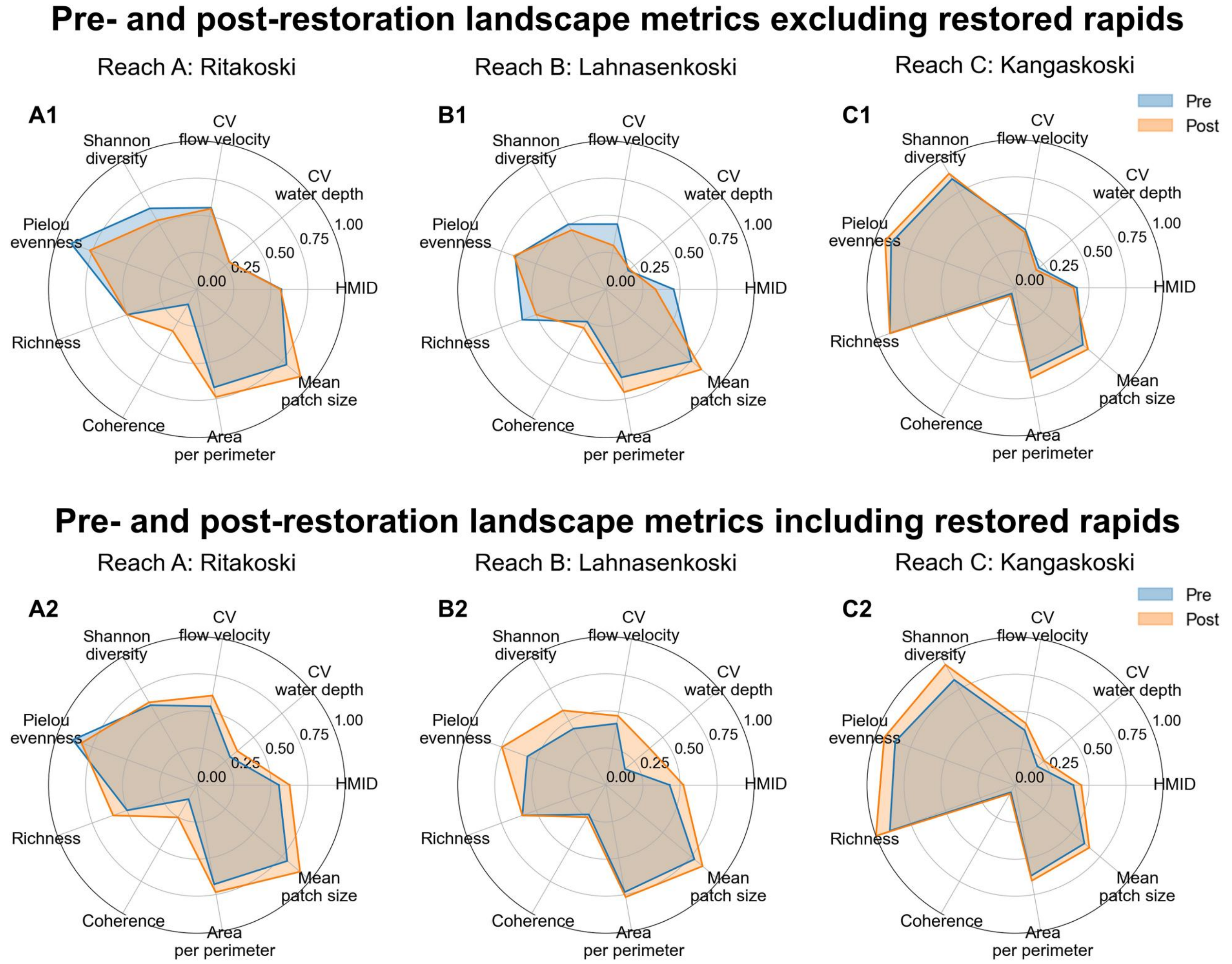


**Figure 7.** Radar plots of scaled [0;1] landscape metrics for Reaches A–C under pre- and post-restoration conditions, excluding (A1–C1) and including (A2–C2) restored rapids as additional mesohabitat.

S5, B1; Figure 6, B1 and B3), whereas post-restoration maxima were located adjacent to the restored rapids (Figure S5, B3; Figure 6, B2 and B4). The pre-restoration velocity distribution exhibited a longer high-velocity tail (maximum 0.68 m/s) compared to post-restoration conditions (maximum 0.43 m/s; Figure 5, B1). Pre-restoration conditions were characterized by small, localized fast-flow patches, whereas post-restoration conditions exhibit larger patches with more moderate velocities, coinciding with the loss of the *fast* × *intermediate* habitat class (Figure 6, B3). Flow structure also changed from a single-threaded current before restoration to a subdivided flow with partial diversion toward the right bank, creating a low-flow zone in the reach centre (Figure S5, B3). Local water depth reductions near the hydropower plant outlet reflect morphological reconfiguration from restoration-related backfilling (Figure 5, B2; Figure S5, B4).

In Reach C, the velocity distribution is bimodal, reflecting a high-velocity main channel and a low-flow side channel. Prior to restoration, the main flow was conveyed through the hydropower plant (Figure S5, C1). Following restoration, the former spillway became the main channel (Figure S5, C3). The redistribution of fast-flow patches confirms this channel shift (Figure 6, C3–C4). The channel shift increased area-wise flow velocities (Figure 5, C1) while reducing peak velocity from 1.48 m/s near the former hydropower plant outlet (Figure 6, C1) to 1.17 m/s post-restoration. The 450 m long Reach C contains all nine reach-wise deterministically defined habitat classes (Figure 4; cf. 3.4).

Overall, restoration induced a clear spatial current shift in Reaches B and C. Despite area-wise increased flow velocities, peak flow velocities decreased following dam removal and river restoration.

### *4.2. Mesohabitat quality proxies following dam removals and river restoration*

Deterministically classified pre- and post-restoration hydraulic patches (Figure 6, A3–C4) were used to calculate landscape metrics quantifying the effects of dam removal and river restoration per reach. In a first step, metrics were evaluated for mesohabitats delineated by PatchBuilder downstream of the rapids only. Radar plots (Figure 7, A1–C1) and metric values (Table S6) show increases in structural connectedness (coherence, area-per-perimeter, and mean patch size) across all reaches, indicating improved habitat connectedness after restoration. Hydraulic heterogeneity metrics remained largely unchanged in Reaches A and C, whereas in Reach B CV flow velocity and HMID decreased by 47% and 41% respectively. This decline goes along with a richness drop by one habitat class (Figure 7, B1) due to the loss of the small *fast* × *intermediate* mesohabitat near the former hydropower plant outlet (Figure 6, B3), which previously exhibited the highest peak velocities (Figure S5, B1). In Reach B, Shannon's Diversity Index decreased by 9%, while Pielou's Evenness Index remained stable. In Reach A both Shannon's Diversity Index and Pielou's Evenness Index decreased post-restoration by 14% whereas in Reach C both metrics increased by 5%.

The resulting patch delineations for $n = 10–100$ (Figure S4) showed that the three hydraulic heterogeneity metrics, based on patch-wise mean and standard deviation of flow velocity and water depth, varied the least, while diversity and spatial connectedness metrics were more sensitive to the number of patches, reflecting their dependence on the underlying deterministic patch classification.

In a second step, the restored rapids were included as additional mesohabitat to approximate their impact on overall habitat quality proxies (cf. 3.2). Radar plots including rapids (Figure 7, A2–C2) show post-restoration value increases in 25 of the 27 metric–reach combinations, indicating a strong positive effect of rapids on overall habitat quality proxies. Only Pielou's Evenness Index in Reach A decreased marginally by 7%, and richness in Reach B remained unchanged.

Hydraulic heterogeneity increased substantially across all reaches, with HMID rising by 36%, 47%, and 25% in Reaches A, B, and C, respectively (Table S6). This increase is driven by the distinct hydraulics of the rapids, which combine high flow velocities with shallow water depths and thereby broaden the flow velocity–water depth spectrum represented in the classified patch mosaic. The rapids, classified as *very fast* × *very shallow*, added one habitat class, increasing overall post-restoration relative richness by +0.10 in each reach. Despite the loss of the pre-restoration *fast* × *intermediate* habitat class in Reach B, inclusion of rapids maintained relative richness while altering habitat composition. Reach C exhibited the full post-restoration richness, with ten habitat classes spanning the entire flow velocity–water depth spectrum (Figure 4). Overall, the inclusion of the restored rapids substantially enhanced habitat quality proxies particularly in hydraulic heterogeneity and diversity across all study reaches (Figure 7, Table S6).

The results of the ±20% sensitivity analysis (Figure S7) of post-restoration flow velocity and water depth confirmed the robustness of the rapids habitat classification and the resulting landscape metric values. Across all three reaches, the rapids patch retained the novel habitat class *very fast* × *very shallow*, as flow velocity remained above and water depth below the reach-specific classification boundaries of the downstream AOI patches (Figure 4). Spatial connectedness and diversity metrics stayed unaffected by ±20% varied post-restoration flow velocity and water depth within the rapids, while hydraulic heterogeneity metrics showed only negligible changes (Figure S7).

## 5. Discussion

In this study, we developed a step-by-step framework (Figure 3) based on hydroacoustic ADCP data to delineate contiguous, homogeneous hydraulic patches and to quantify pre- and post-restoration habitat quality proxies using ecologically relevant landscape metrics. In the following we discuss the key findings, highlight the novelty, acknowledge limitations and uncertainties and outline the broader applicability of the framework.

### 5.1. Key findings

The delineated mesohabitats captured spatial patterns of flow velocity and water depth with high spatial detail, reflecting homogeneous hydraulic conditions within clearly defined patch boundaries. Distinct hydraulic features, such as peak flow velocities near hydropower plant outlets, were effectively represented. The resulting hydraulic patches provide a spatially explicit representation of physical habitat composition and are well suited to support field-based ecological surveys and habitat-oriented monitoring (Parasiewicz 2007; Parasiewicz et al. 2013).

Interpreting these patches ecologically requires context. Habitats near operating hydropower plants may offer reduced suitability for aquatic species, as sub-daily flow variability associated with hydropower regulation alters the availability and functionality of habitat structures (Wolter et al. 2016; Bozeman et al. 2025), limiting the effective habitat accessible to organisms with limited mobility (Bovee et al. 1998). Accordingly, observed habitat changes require context-specific interpretation with respect to their biological relevance (Bovee et al. 1998; Wolter et al. 2016; Bozeman et al. 2025).

The three metric sub-groups (Table 1) each provide a complementary perspective on changes in habitat quality proxies, and the restoration response differed in character across groups.

Hydraulic heterogeneity metrics captured variations in flow velocity and water depth directly relevant to aquatic habitat suitability. When only downstream mesohabitats were considered, hydraulic heterogeneity remained largely unchanged in Reaches A and C and decreased in Reach B. In contrast, when restored rapids were included as additional mesohabitat, however, hydraulic heterogeneity increased consistently across all study reaches, expanding the available flow velocity–water depth spectrum. Such increases are widely associated with improved proxies of habitat quality, reversal of channel homogenization, and enhanced ecological integrity in regulated rivers (Woolsey et al. 2007; Gostner et al. 2013; Belletti et al. 2017).

Diversity metrics followed the same pattern. Considering the mesohabitats downstream of the rapids alone, two out of three diversity metrics declined post-restoration in Reaches A and B, whereas Reach C exhibited a slight increase of 5% in both Shannon's Diversity Index and Pielou's Evenness Index. However, when restored rapids were included, eight out of nine diversity metric–reach combinations increased clearly across the study reaches.

Structural connectedness metrics, in contrast, increased post-restoration regardless of whether rapids were included (Figure 7, Table S6), indicating a reorganization toward larger and more connected mesohabitats. Because the three study reaches are spatially separated, these spatial metrics cannot capture the additional, overarching ecological benefits of restored rapids for longitudinal river continuity between reaches formerly fragmented by dam infrastructure.

Even without accounting for this river continuum impact, the inclusion of restored rapids indicates a strongly positive effect on overall habitat quality proxies. Including the restored rapids as additional mesohabitat led to a post-restoration increase in 25 of the 27 metric–reach combinations, with hydraulic heterogeneity (HMID) increasing by 36%, 47%, and 25% in Reaches A, B, and C, respectively, and relative richness by +0.10, corresponding to one additional habitat class, in each reach. Taken together, these results emphasize the importance of restoring hydraulically diverse habitats to reverse channel simplification, mitigate habitat loss and re-establish the heterogeneity that characterises a functioning riverscape (Allan 2004; Reid et al. 2019; Dudgeon and Strayer 2025).

## 5.2. Previous research and novelty

A major strength of this study is the use of unique field datasets fulfilling key criteria for restoration impact assessment, namely temporally capturing pre- and post-dam removal conditions, spatially overlapping survey areas, and comparable boundary conditions ensured by similar discharge rates. Despite increasing efforts to evaluate river restoration outcomes, ecological responses remain insufficiently resolved, particularly where biotic data or target species assessments are unavailable. This underscores the need for spatially explicit habitat analysis and quantitative indicators as important first steps toward understanding potential ecological response (Parasiewicz 2007; Woolsey et al. 2007; Palmer and Ruhi 2019).

This study advances current research by applying meso-scale habitat delineation to a non-wadable Nordic lowland river, whereas previous applications have focused on mostly wadable gravel-bed rivers (Vezza et al. 2014; Tamminga and Eaton 2018; van Rooijen et al. 2021). In contrast to the widespread use of two-dimensional hydraulic model outputs for habitat analysis (Pasternack 2011; Tonina and Jorde 2013), our results demonstrate that ADCP-derived hydraulic data provide a viable and efficient alternative for meso-scale habitat delineation in larger rivers.

Although landscape metrics are well established in terrestrial ecology, their application to aquatic environments remain rare, and their potential for evaluating river restoration outcomes is still largely unexplored (Weber et al. 2025). Our findings confirm that landscape metrics offer a flexible and informative framework for quantifying hydraulic heterogeneity, spatial connectedness, and diversity at the riverine meso-scale in an intuitive and ecologically meaningful way.

## 5.3. Limitations and uncertainties

Several sources of uncertainty must be acknowledged. A limitation of this study is the reliance on a single discharge rate per study reach for both pre- and post-restoration assessments. Although datasets were carefully selected to ensure the most comparable discharge conditions between the pre- and post-restoration surveys per reach, this approach remains static in nature and cannot capture the full range of hydrological variability within the system. Consequently, the observed hydraulic changes and delineated mesohabitats may not be fully representative across the full flow spectrum. To provide broader hydrological context, we provide a long-term discharge time series and flow duration curve in Figure 2 to better contextualise the discharge conditions under which the ADCP datasets were acquired relative to overall flow regime.

Variations in ADCP measurement locations between pre- and post-restoration surveys and interpolation uncertainties in data-scarce areas may influence local habitat delineation. Furthermore, the choice of grid resolution ($2 \times 2$ m) may influence the results of the delineated patches and habitat quality proxies, as grid size and sample density have been shown to affect hydraulic habitat computations (Stähly et al. 2018; Papaioannou et al. 2020; Farò et al. 2023). However, since a consistent resolution was applied across pre- and post-restoration datasets, the comparative assessment of pre- and post-restoration conditions remains valid. The ADCP-based approach excludes the surveying of shallow areas such as close to river banks, in floodplains and rapids, thereby not covering the full wetted channel and limiting habitat representation and the derived landscape metrics. To address this limitation, parts of the restored rapids where pre- and post-restoration hydraulic conditions were homogeneous were incorporated as additional mesohabitat by approximating prevailing pre- and post-restoration hydraulic conditions.

Hierarchical clustering requires the number of patches $n$ to be set in advance, ideally matching the true number of hydraulic patches in the reach, which is generally unknown. We addressed this by testing a range of $n$ values and selecting the one whose patch configuration and shape best represented the pre- and post-restoration hydraulics from field inspections. A sensitivity analysis across a wider range of patch numbers could help identify which landscape metrics are most sensitive to the choice of $n$ (Figures S3 and S4).

The deterministic, rule-based habitat classification applied here ensures transparency, reproducibility, and straightforward interpretation of physical habitats, which is beneficial for communication with stakeholders. However, fixed classification thresholds may oversimplify continuous hydraulic gradients, and habitat classes are not transferable between reaches due to normalization of hydraulic variables per reach. In particular, these class boundaries may not coincide with ecologically meaningful thresholds, and transitions between adjacent classes are discrete rather than gradual (Legleiter and Goodchild 2005; Parasiewicz 2007).

The flow velocity and water depth values selected to characterize the rapids mesohabitat represent approximations of the hydraulic conditions for the given acquisition dates (Table S1). ADCP measurements within the rapids were impeded by the turbulent, fast flow conditions and shallow water depth typical of rapids environments. Furthermore, safety considerations restricted the ability of field personnel to bank-side ADV measurements only. As a result, the hydraulic post-restoration values used in this study may not fully capture the range of flow velocities and water depths present within the rapids. To account for this uncertainty, a sensitivity analysis was performed, which confirmed that the landscape metrics are robust to ±20% variation in the fixed hydraulic values assigned to the post-restoration rapids patch, as the novel habitat class was preserved under all tested variations (Figure S7). Despite the uncertainties, and when compared with micro-habitat analyses, meso-scale habitat analyses allow the integration of a broader range of environmental variables and better reflect the habitat use of highly mobile organisms such as fish, making them a more ecologically relevant scale for habitat quality assessment (Vezza et al. 2014; Wolter et al. 2016; Wegscheider et al. 2020). In addition, they facilitate more rapid field surveys over longer river reaches (Parasiewicz 2007; Parasiewicz et al. 2013). However, meso-scale habitat analysis may come at the expense of fine-scale habitat detail at the patch-scale crucial for sessile organisms, smaller species, or specific life stages (Bätz et al. 2023, 2025; Farò et al. 2023).

## 5.4. Future perspectives and broader applicability

The proposed framework is conceptually grounded in the riverscape perspective, in which rivers are treated as spatially explicit mosaics of connected physical habitat patches, and is therefore transferable across river environments differing in size, morphology, and flow regime. To maintain the approach straightforward and easy to interpret, physical habitat was defined solely by water depth and flow velocity, deliberately excluding other potentially relevant variables such as temperature, cover, or substrate. Among these, substrate is particularly relevant, being both ecologically meaningful and directly affected by dam removal through possible changes in sediment transport. Incorporating substrate characterization, for example through grain-size mapping from field surveys or close-range remote sensing, would enrich the habitat assessment and represents an important direction for future work.

The post-restoration surveys presented in this study represent an early assessment of reach adjustment, and habitat conditions are expected to undergo further modification as hydro-morphodynamic processes continue to reshape the restored reaches over extended timescales. Furthermore, a submerged boulder sill at the upstream head of each reconstructed rapids maintains pre-removal water surface levels, which likely impose an impediment to sediment transport and partially constrains longitudinal sediment continuity through the restored reaches. Investigating the potential implications of these structures for substrate composition and bed material sorting represents a promising direction for subsequent research but was beyond the scope of the present study. To capture the long-term trajectory of hydro-morphodynamic adjustment and to evaluate the associated implications for habitat composition and quality proxies, repeated surveys over longer monitoring intervals are needed. A further advancement of abiotic habitat assessment could be a time-series approach to further assess spatio-temporal habitat dynamics under variable discharge (Wallis et al. 2012; Bätz et al. 2023, 2025). Applying hydrodynamic models to simulate hydraulic conditions across a wider range of discharges, could help to overcome the inherent limitations of field-based ADCP surveys, which are constrained to the flow conditions present at the time of measurement.

Similarly, biological or taxon-specific information was not incorporated, as the objective was to delineate and quantitatively analyse abiotic mesohabitats. However, the framework is flexible and could be extended to account for species-specific habitat preferences by defining hydraulic thresholds or suitability classes based on species requirements (Bovee et al. 1998; Parasiewicz 2007; Parasiewicz et al. 2013; Vezza et al. 2014). Under the assumption that distinct habitat types support different species, habitat assessment methods can provide a rapid and cost-efficient, though less precise, alternative to direct biodiversity assessments (Thomson et al. 2001).

## 6. Conclusion

This study set out to assess how dam removal and river restoration impact physical habitat composition by delineating and classifying spatially contiguous, homogeneous mesohabitat patches from hydraulic field data and by quantifying habitat quality proxies using landscape metrics. By addressing habitat composition, habitat quality proxies, and the contribution of restored rapids on overall habitat quality proxies, the proposed framework fulfilled all three research aims and enabled a robust impact assessment to assess the riverscape of three dam removal sites at Hiitolanjoki River.

The mesohabitat delineation successfully captured spatial patterns of flow velocity and water depth and provided the physical habitat composition pre- and post-restoration. Landscape metrics revealed that restoration outcome evaluation on habitat quality proxies depends strongly on whether newly created habitats are considered. While downstream mesohabitats alone showed variable responses, the inclusion of restored rapids clearly enhanced hydraulic heterogeneity metrics and most diversity metrics for the study reaches. This insight underscores the role of restoring hydraulically diverse features for reversing habitat homogeneity and fragmentation. These changes are widely associated with improved ecological integrity and increased potential to support diverse species assemblages and ecosystem functioning.

Beyond site-specific findings, this study demonstrates that habitat-based assessments provide valuable tools for predicting and evaluating physical habitat responses to restoration measures, supporting both restoration design and outcome evaluation. Landscape metrics proved to be a straightforward and objective means of quantifying restoration benefits, offering clear advantages for long-term monitoring and comparative assessments.

Furthermore, this study demonstrates the novel applicability of a field-based, hydroacoustically driven approach to non-wadable lowland rivers, highlighting its potential for transfer to diverse river environments without reliance on hydrodynamic model outputs. The here developed framework of meso-scale habitat delineation linked with landscape metrics can be transferred to other river restoration contexts independent of the river environment, if boundary conditions such as discharge, and metric selection are carefully aligned with site-specific characteristics. From a broad perspective the findings underscore the need to actively restore hydraulically diverse habitats and to evaluate restoration outcomes from a riverscape perspective.

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## Author contributions

CRediT: **Kerstin Schlobies**: Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Project administration, Resources, Software, Validation, Visualization, Writing – original draft, Writing – review & editing; **Erik van Rooijen**: Conceptualization, Methodology, Resources, Supervision, Validation, Writing – review & editing; **Davide Vanzo**: Conceptualization, Methodology, Resources, Supervision, Validation, Writing – review & editing; **Eliisa S. Lotsari**: Conceptualization, Data curation, Funding acquisition, Investigation, Project administration, Resources, Supervision, Validation, Writing – review & editing.

## Disclosure statement

To support the development of this work, the authors used AI-based tools such as ChatGPT and DeepL for coding assistance and for language-related tasks such as grammar checking, phrasing, and text structuring. All AI-assisted outputs were reviewed and revised by the authors, who take full responsibility for the content and conclusions of the manuscript. The authors declare no potential conflicts of interest.

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## Data availability statement

Data available on request from the authors.

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