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ECOLOGICAL FLOWS AS A DRIVER FOR FUTURE HYDROPOWER DEVELOPMENT

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ABSTRACT

At the intersection of environmental protection and energy transition, Italy is called to find new approaches to safeguard river ecosystems while modernizing its hydropower infrastructure. Achieving this balance under the new Ecological Flow (EF) framework requires integrated strategies that reconcile ecological integrity with energy efficiency. This study evaluates the eco-hydrological and operational implications of redefining EFs for run-of-river (RoR) plants, exploring synergies between new EF regimes and potential plant re-powering through increased maximum water abstraction capacity. Focusing on three Alpine rivers (Ayasse, Brenve, and Savara), EF design was based on the mesohabitat simulation model (MesoHABSIM) and on the Habitat Integrity Index (IH), an ecologically meaningful indicator composed of five quality classes. Hydropower performance was assessed by computing the corresponding total volume of water diverted to turbines. Results showed that improving habitat quality from "Bad" to "High" required base flow (BF) increases of 1.6-9.4 times current rates, reducing diverted water volumes by 8-28%. However, coupling higher BF with expanded water abstraction capacity enhanced hydropower production by 124-169% while preserving river ecological integrity. This framework supports the design of RoR configurations that harmonize ecological sustainability, economic feasibility, and climate resilience.

Keywords: *Ecological Flows, Hydropower repowering, Habitat Integrity Index, MesoHABSIM, Alpine rivers.*

1. Introduction

As countries intensify efforts to reduce greenhouse gas emissions, the global demand for renewable energy continues to rise. Within this transition, hydropower remains a key contributor to renewable electricity generation, offering a unique combination of reliability, operational flexibility, and a near-zero carbon footprint (Zarfl et al., 2015). Its economic competitiveness and stable performance make it a key driver in the shift toward a fully decarbonized energy system (Aubin et al., 2025).

However, diverting or storing water for hydropower can substantially affect river ecosystems (He et al., 2024). Dams and weirs modify hydrological and sediment regimes, and alter the organic material supply in the downstream reaches, compromising habitats and diminishing aquatic biodiversity (Poff & Zimmerman., 2010). To mitigate these impacts, the concept of Environmental Flows (EF) has been developed since the 1970s. Italy introduced Minimum Flow (MF) requirements in 1989, but static MF releases often failed to provide meaningful ecological protection. More recently, the European Union promoted a broader EF framework, considering temporal variability, seasonality, sediment transport, and species' habitat requirements. In 2017, the Italian Ministry of Environment and Energy Security formalized this approach through the Decree DD 30/STA 2017, which aimed to mimic natural flow variation by establishing base flows (BF) and controlled high-flow events to support river ecosystems.

Constructed primarily between the 1920s and 1970s, most of Italy's large and medium hydropower plants now face challenges related to aging infrastructure and limited operational flexibility (Stucchi et al., 2023). Originally designed for stable, and predictable energy demand, many plants lack the adaptive capacity needed for integration with variable renewable sources and modern energy markets. Enhancing hydropower flexibility through re-powering, control system upgrades, and operational improvements has become a strategic priority to support both renewable energy targets and grid stability. This study evaluates how newly established EF regimes influence both river habitats and hydropower production, while exploring opportunities for future re-powering. Using three Alpine streams in the Aosta Valley as case studies, it integrates ecological and operational analyses across multiple EF release scenarios and plant configurations. River ecological integrity was assessed using the MesoHABitat SImulation Model (MesoHABSIM; Parasiewicz, 2007) in combination with the Habitat Integrity Index (IH; Vezza et al., 2017). The results provide practical insights into sustainable hydropower strategies that align renewable energy production with the conservation of mountain river ecosystems.

2. Materials and Methods

2.1. Study area

The study was conducted considering three Alpine streams, Ayasse, Brenve, and Savara, located in the Aosta Valley, Northwestern Italy. These short, steep watercourses (3.7-27 km; 7-15% slope) exhibit step-pool or cascade morphologies and coarse gravel-boulder substrates, with minimal anthropogenic disturbance. All sites host run-of-river (RoR) systems with small weirs and negligible storage, representative of most Italian hydropower installations (Galletti et al., 2025). The area has an Alpine-Continental climate, with winter low-flow conditions driven by freezing, snow accumulation, and glacier influence.

2.2. Habitat description and analysis

Habitat assessment was performed using the MesoHABSIM, a physical habitat modeling framework that quantifies spatio-temporal variations in fish distribution as a function of in-stream flow and channel morphology (Vezza et al., 2017). The approach involves detailed mapping and characterization of hydro-morphological units (HMUs; e.g., pools, riffles, rapids; Belletti et al., 2017) to evaluate habitat availability for target species under different discharge conditions. For each surveyed discharge, available habitat is then estimated using species-specific habitat suitability criteria (HSC) that incorporate local physical attributes of HMUs, including depth, velocity, substrate, and cover (Vezza et al., 2017). Brown trout (*Salmo trutta*) and marble trout (*Salmo marmoratus*), the only fish species inhabiting the investigated streams, were selected as ecological targets. Habitat availability was assessed for the rearing and growth bioperiods (adults and juveniles; Vezza et al., 2012) and for the critical spawning period (adult only).

Habitat simulations were performed using SimStream-Web, an online platform that supports the MesoHABSIM methodology (https://mesohabsim.isprambiente.it/app/home/). The platform generates habitat-flow rating curves, which allow streamflow time series to be expressed in terms of habitat availability. By comparing a reference eco-hydrological scenario (without hydropower operation) with an altered one (reflecting hydropower plant activity), the platform computes the Habitat Integrity Index (IH). This index quantifies the deviation between reference and altered conditions through two sub-indices: The Index of Spatial Habitat availability (ISH) – representing the mean loss of habitat; and the Index of Temporal Habitat availability (ITH) – analyzing the duration and frequency of habitat stress events (i.e., periods when habitat availability falls below the 97th percentile of the reference series; see Vezza et al., 2017; Vassoney et al., 2019 for details). Both ISH and ITH range from 0 to 1, with lower values indicating stronger degradation. The overall IH is defined as the minimum of the two sub-indices among all target species. According to the Vezza et al. (2017) and consistent with the European Water Framework Directive, IH values are divided into five habitat quality classes (High, Good, Moderate, Poor, and Bad) using 0.2 incremental thresholds.

2.3. Ecological flows and hydropower re-powering

To evaluate the effects of EF on hydropower production and re-powering potential, both base flow and maximum water abstraction capacity (Max Flow) were varied to defined specific altered time series (scenario). Two scenario groups were defined: Group A considered BF changes only (6 scenarios; **Fig. 1A**), while Group B combined BF variations with increased water abstraction capacity (6 scenarios; **Fig. 1B**). For **Fig. 1A** and **1B**, Scenario 1 represented the current conditions (constant minimum flow and existing turbine capacity), whereas Scenarios 2-6 incorporated monthly variable BF (Group A) and, for Group B, combined with increased turbine capacity, assumed up to 250% higher than current levels. Each scenario aimed to achieve a

specific habitat quality class (Bad to High) based on the IH index. Hydropower production was estimated from the total volume of water diverted to turbines, based on the difference between the reference (natural flow regime) and the altered scenarios. Reference streamflow was generated using the Continuum distributed hydrological model (Silvestro et al., 2012), producing a 13-year daily record (2008-2021).

3. Results

Three to four river surveys were conducted at each site, covering a range of discharges from low-flow conditions (99th percentile of the reference time series) to medium flows (up to 15th percentile of the reference time series). Habitat-flow rating curves were generated using SimStream-Web for all sites, species, and bioperiods. In the Ayasse Stream, adult trout habitat increased monotonically with discharge, whereas juvenile and spawning habitats exhibited non-monotonic patterns, peaking at lower flows (~0.5 m³/s). The Brenve Stream, the smallest of the three, exhibited monotonically increasing curves for all bioperiods, indicating consistent habitat availability gains with flow. In contrast, habitat availability for all targets in the Savara Stream peaked between 1 and 2.5 m³/s, with higher flows leading to a decline in suitability due to excessive velocities.

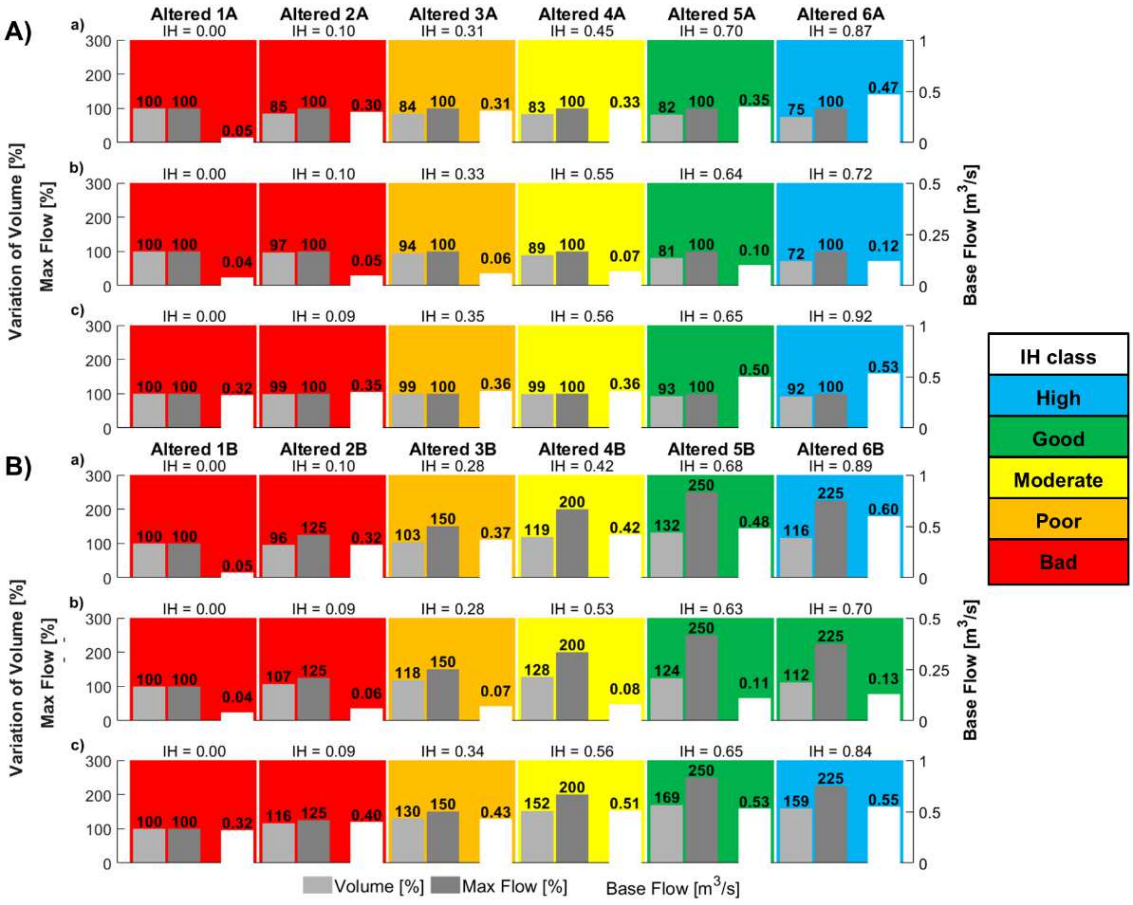

Fig. 1. Results of the scenario analysis for the three study sites: a) Ayasse, b) Brenve, and c) Savara streams. Group A) scenarios (top panels) explore variations in base flow (BF) under the current maximum water abstraction capacity, while Group B) scenarios (bottom panels) combine changes in BF with increased water abstraction capacity to assess re-powering potential. For Figures 1A and 1B, Scenario 1 represented the current conditions (constant minimum flow and existing turbine capacity). The grey bars (left y-axis) illustrate the percentage change in total diverted volume (light grey) and maximum water abstraction capacity (dark grey). The white bar (right y-axis) shows the mean BF released to the river when diversion operates below its maximum capacity. Background colours indicate habitat quality classes based on the Habitat Integrity Index (IH).

Based on the resulting habitat-flow rating curves and considering the reference flow time series, 12 altered series were defined for each site. Altered scenario analyses evaluated the effects of BF and maximum water abstraction capacity on habitat quality and hydropower production. Group A (varying BF only) showed that achieving a "High" IH class required increasing BF from 1.6× (Savara) to 9.4× (Ayasse) current values, reducing turbine-diverted volumes by 8-28% (**Fig. 1**A). Group B (combining varying BF and increased maximum water abstraction capacity) enabled hydropower production gains of 124-169% for "Good" habitat quality (**Fig. 1**B). Concentrating withdrawals during high-flow periods, impacts on fish habitat were reduced. Interestingly, trade-offs emerged for high maximum water abstraction values: further IH improvements required reducing turbine withdrawals, particularly in Ayasse and Savara Streams (ALTERED 6B; **Fig. 1**B).

4. Discussion and Conclusions

Our study shows that hydropower re-powering through increased maximum water abstraction capacity can be sustainable when combined with carefully designed EF regimes. EF releases which varied on seasonal or monthly scale are essential to maintain habitat availability for all fish species and bioperiods. Maximizing water abstraction capacity without considering ecological impacts can compromise river integrity, while EF strategies ignoring technical and economic constraints may be impractical. Sustainable hydropower depends on achieving a balance between energy generation, ecological preservation, and economic feasibility.

EF and maximum water abstraction thresholds should be adapted to local conditions, as each hydropower plant functions within a unique eco-hydro-morphological context. Increasing water abstraction capacity allows greater water withdrawals during high-flow periods, reducing ecological stress while boosting energy generation, whereas EF releases safeguard habitat integrity during low flows. Coupling increased turbine capacity with dynamic EF regimes creates synergies: river habitats benefit from ecologically meaningful flows and high-flow pulses, while hydropower operators can exploit periods of hydrological abundance. This alignment is particularly valuable in the Alpine context, where summer snowmelt generates peak hydropower production precisely when electricity demand for air conditioning reaches its highest levels. This integrated approach supports adaptive, sustainable hydropower where ecological restoration and energy objectives are mutually achievable.

The urgency of adaptive management is heightened under climate change, which alters Alpine hydrology through warming, glacier retreat, and shifting precipitation patterns, affecting both hydropower reliability and ecosystem resilience. Many aging RoR plants, often with limited storage, could better utilize short-term hydrological peaks and more variable summer/autumn flows via enhanced water abstraction capacity. Combined with climate-informed EF strategies, this approach ensures technically robust, ecologically sound, and economically viable hydropower operations. The future of hydropower in Italy, and similar regions with aging infrastructure, depends on adopting adaptive, ecologically informed management strategies that ensure both clean energy production and resilient river ecosystems.

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