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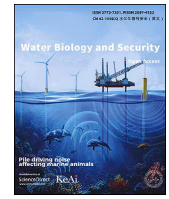

The role of ecohydraulics in addressing the freshwater biodiversity crisis

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ABSTRACT

Ecohydraulics is a scholarly discipline and community of practice that represents the intersection of ecology and hydraulics/fluid dynamics. Although understanding the intersection of ecology and hydraulics is of fundamental interest, it is also highly relevant to the management and conservation of freshwater life and ecosystems, and consistent with calls for more integrative thinking. Here we provide an overview of the ways in which ecohydraulics has the potential to contribute to supporting the protection and recovery of freshwater biodiversity. For example, ecohydraulics can be used to identify environmental flows that benefit aquatic life while enabling hydroelectric generation. In the context of invasive species, ecohydraulics can be used to identify trapping designs that select invasive species whereas for reducing exploitation, it can be used to inform selective fishing gear designs. In terms of water quality management, ecohydraulics can inform the design of stormwater infrastructure that supports freshwater life. Habitat restoration can be guided by integrating morphodynamics and the habitat needs of species of interest or to ensure that aggregate water extraction is done in a manner and at sites that do not degrade freshwater ecosystems. Ecohydraulics also informs the maintenance or re-establishment of river connectivity through design of fish passage facilities. In summary, ecohydraulics has much to offer in the support of efforts to maintain and restore freshwater biodiversity. Doing so will require continued investment in fundamental and mission-oriented science, but also an emphasis on equipping practitioners with knowledge to implement actions that benefit freshwater biodiversity and people.

1. Introduction

By all accounts, freshwater ecosystems and their constituent biodiversity are doing poorly (Albert et al., 2021) to the point where a “crisis” has been declared (Harrison et al., 2018). Indeed, freshwater ecosystems are considered to be impacted at a level equal to that of tropical rainforests that have been clear-cut and burned. The recent WWF Forgotten Fishes report reveals that approximately one-third of freshwater-dependent fishes are imperiled (WWF, 2021). Moreover, the WWF Living Planet Report reveals that for populations of freshwater animals (spanning invertebrates and vertebrates) tracked since 1970, there has been an average decline of more than 80 % (WWF, 2024). The reasons for these declines are numerous and include longstanding drivers such as pollution, invasive species, habitat loss/alteration, water

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extraction, fragmentation, and climate change (Dudgeon et al., 2006). In addition, there are many emerging challenges (e.g., pathogens, declining calcium, harmful algal blooms), and their combination with the aforementioned persistent challenges that further pressure freshwater life (Reid et al., 2019). Beyond the inherent value in such losses, humans are also being negatively affected given that humans depend on freshwater life for food security, livelihoods, culture, and much more (Lynch et al., 2023).

In 2018 the WWF led the development of an Emergency Recovery Plan for freshwater biodiversity in recognition of the dire state of affairs (Tickner et al., 2020). The Emergency Recovery Plan for global freshwater biodiversity aims to reduce the risk of freshwater biodiversity loss through six priority actions. In recognition that those actions are all rather "high level" there have been efforts to elaborate on them and identify specific response measures (e.g., Cooke et al. In Press; Piczak et al. In Press; Thieme et al. In Press). Those actions are all underpinned by evidence and will require the work of many including scientists, practitioners, politicians, stakeholders, and rights holders (Twardek et al., 2021; Cooke and Birnie-Gauvin, 2022; Birnie-Gauvin et al., 2023). In some cases, the evidence base for the actions is quite clear whereas in other cases there remain knowledge gaps that impede evidence-informed action (Flitcroft et al., 2019; Harper et al., 2021; Maasri et al., 2022). What is clear is that there is much urgency to the freshwater biodiversity crisis (Birnie-Gauvin et al., 2023) as well as creativity to develop solutions for today and tomorrow (Strayer and Dudgeon, 2010; Lynch et al. In Press).

Ecohydraulics is a scholarly discipline and community of practice that represents the intersection of ecology and hydraulics/fluid dynamics (Rice et al., 2010; Nestler et al., 2016). The domain extends from "in water" to riparian systems and includes both biological and physical elements that span spatial and temporal scales (Gosselin et al., 2019). The discipline of ecohydraulics[1] has evolved quickly such that there are now conferences, and several journals (see Kemp and Katopodis, 2016) focused on this topic (see Casas-Mulet et al., 2016). Although understanding the intersection of ecology and hydraulics is of fundamental interest, it is also highly relevant to the management and conservation of freshwater life and ecosystems (Katopodis, 2012) and consistent with calls for more integrative thinking (Geist, 2011). As such, here we provide an overview of the ways in which ecohydraulics (as a discipline and community of practice) has the potential to contribute to realizing the Emergency Recovery Plan for freshwater biodiversity. The purpose of this article is to identify opportunities for those active in ecohydraulics to support curve-bending activities to benefit freshwater biodiversity and people. The examples provided are not intended to be prescriptive nor comprehensive/exhaustive, rather they are to inspire those with expertise in ecohydraulics to consider what they have to offer given the urgent need for science-based solutions to the freshwater biodiversity crisis. Indeed, although we have assembled a diverse group of co-authors, we do not want to constrain the creativity of readers. This is not a comprehensive review but rather a perspective article and thus that perspective is influenced by the positionality of the authorship team. The authorship team spans regions, expertise, and sectors (government, industry, academia) although we acknowledge that a broader and more diverse suite of participants (especially from the global south) may have identified other ways in which ecohydraulics are relevant to freshwater biodiversity conservation. The paper is organized around the six actions (Fig. 1) identified as foundational to the Emergency Recovery Plan.

[1] We also acknowledge the related disciplines of ecohydrology (Janauer, 2000) and ecological engineering (Mitsch and Jørgensen, 2003) but do not wish to discuss philosophical or practical differences or similarities with ecohydraulics. For the purpose of this paper, we focus on ecohydraulics embracing the reality that there is a blurred line among these domains of research and practice.

2. Action 1: Accelerate implementation of environmental flows

Environmental flows (e-flows) science has evolved over the course of the last few decades from minimum flow prescription often leading to hydrograph flat-lining to a more comprehensive definition found in the Brisbane declaration (Arthington et al., 2018). These include considering the inter-annual flow variability that is crucial for species with longer life cycles (e.g., riparian vegetation, Rivaes et al., 2017) and the sediment dynamics crucial for downstream ecological processes (De Jalón et al., 2017). The scientific consensus on this broader context in which water quality, flow variability and timing of events are included is strong and growing (e.g., Acreman and Ferguson, 2010; Liu et al., 2016; Boavida et al., 2018; St-Hilaire et al., 2021). In their review, Poff et al. (2017) stated that the rapid implementation of e-flows requires a shift in emphasis, from the current dominance of statistical flow-ecology models to better, more comprehensive studies of processes that explain hydrologic controls on ecological dynamics. They also advocate for a shift in spatial scale from the current emphasis on river reach to broader, basin-wide scale approaches (Paredes-Arquiola et al., 2013; Poff et al., 2016; Solans et al., 2024).

Ecohydraulics is central to the development, improvement and implementation of e-flows, because it is a pivotal piece of habitat science and modelling, helping to define flow-ecology relationships (e.g., Hayes et al., 2018; Boavida et al., 2020a; Sedighkia et al., 2021). By integrating these methodological frameworks, multiple tools emerge to advance these conceptual shifts and accelerate e-flow implementation. The science of ecohydraulics has evolved to provide a framework in which many of the key anthropogenic impacts that lead to altered flow regimes can be assessed and offer means of achieving e-flows. However, scientific monitoring over many years, along with e-flow model validations are rare. Yet, these validations are needed to determine the effectiveness of e-flow regimes and assess their success in protecting aquatic life, habitats and productivity (Souchon et al., 2008; Katopodis, 2022).

One key tool to accelerate e-flow implementation across jurisdictions is to continue the development of hierarchical methodological frameworks for e-flow assessment. While the methodological portfolio is well equipped (Tharme, 2003), few methodological frameworks offer a hierarchy which allows for the selection of e-flow determination methods along a gradient of complexity, e.g., from simple analysis of historical flow time series, hydraulic methods, habitat models and holistic approaches. However, many of these methodologies are focused on a bottom-up approach, which often makes their application to a basin-wide scale difficult (Tharme, 2003). Not to mention many of these river basins extend across multiple countries, which would require the collaboration of parties (Tharme, 2003). It is also important to acknowledge that budget and scope are also relevant to tool selection. Moreover, it is critical to consider the importance of intra-annual variability in the flow regime, to maintain biodiversity in different climatic zones (Belmar et al. 2011, 2012). For example, when implementing e-flows in circumpolar countries, winter habitat must be considered as there may be unique variations in hydraulic, morphodynamic and thermal regimes based on ice-free and ice-over conditions (Brown et al., 2011; Katopodis, 2022). By streamlining such methodological frameworks and tools to science and practice, ecohydraulics can enable their application by a range of stakeholders and enhance e-flow implementation. Stakeholder involvement is also central to efficient e-flow implementation emphasizing that ecohydraulics is most powerful when combined with other tools and approaches. Mussehl et al. (2022) pleaded for greater inclusion of individuals and groups outside of the usual management-research dyad. They developed a framework in which stakeholder implication is central and continuous, with a call for constant updates of socio-flow-ecology relationships through monitoring, modelling, and stakeholder engagement. While this process may take longer than implementing simpler approaches, inclusion of key stakeholders is a central step to avoid or minimize conflicts, thereby potentially accelerating e-flow determination through empowerment. In

Fig. 1. Visualization of representative ways in which ecohydraulics can contribute to the six actions of the Emergency Recovery Plan for freshwater biodiversity; (1) Accelerate implementation of environmental flows (image of e-flows as per Creative Commons Attribution-Share Alike 3.0 Unported license, Credit: Burim); (2) Improve water quality to sustain aquatic life (stormwater facilities to reduce pollution; The Municipality of Vaughn, Ontario, Public Access, CCL); (3) Protect and restore critical habitats (stream restoration photo courtesy of California Sea Grant, US government); (4) Manage exploitation of freshwater species and riverine aggregates (aggregate extraction done according to best practices; image via CC BY-NC 2.0, Credit: Olivier Gilard); (5) Prevent and control non-native species invasions in freshwater habitats (selective fish passage; USGS, US Government; Credit: Scott Miehls); (6) Safeguard and restore freshwater connectivity (dam removal; CC BY-NC-SA 2.0, Credit: International Rivers).

response to climate change, the energy transition will introduce a more variable pattern to hydropower production (IEA, 2023), as it integrates increasing shares of variable renewable energy (VRE) sources from wind and solar power. This variability is likely to amplify the frequency and magnitude of hydropeaking, necessitating the accelerated development of adaptive e-flows to mitigate the downstream impacts of pulsed flows at hydropower plants (Boavida et al., 2020a; Batalla et al., 2021). Additionally, legislation and guiding frameworks are crucial for the effective implementation of environmental flows worldwide. The CIS Guidance Document No. 31 (European Commission, 2015), which supports the implementation of the Water Framework Directive (WFD) is an example of that. This document provides comprehensive guidance on defining and maintaining ecological flows, essential for the achievement of the environmental objectives of the WFD in natural surface water bodies. By setting clear, enforceable standards and promoting a consistent approach across member states, such legislation ensures that water management practices are aligned with ecological requirements. Overall, ecohydraulics has much promise for providing data to support evidence-informed decision making related to e-flows.

3. Action 2: Improve water quality to sustain aquatic life

Urbanization and human activities increase the concentration and loads of pollutants in the aquatic environment (Walsh et al., 2005). Pollution and changes to the water chemistry are introduced through point and non-point sources. Conventional urban stormwater management involves flow retention/detention in stormwater ponds, which reduces peak flows and removes contaminants. However, despite their small size, engineered aquatic environments, such as stormwater management ponds and wetlands, experience stratification which can create anoxic conditions leading to inhospitable dead zones (Ahmed et al. 2022, 2023) and even the production of toxic hydrogen sulfide (H_2S) (Chen et al., 2017). One of the most effective means to improve the quality of urban water habitats is to limit and disconnect directly connected impervious lands. Implementing nature-based solutions can create opportunities to intercept and remove pollution from the surface water system. Infiltration practices including sustainable drainage systems (SUDs), permeable pavements, artificial wetlands, and bio-retention provide effective removal of suspended and particulate-bound pollutants (Drake et al., 2014; Spraakman et al., 2020; Tota-Maharaj and Hills, 2023). Additionally, filtration stormwater systems improve water quality by attenuating dissolved pollutants and drastically reducing peak concentrations during runoff events (Sehgal et al., 2023) and reducing the rate of thermal enrichment of runoff (Li et al., 2019). Even more promising is that these stormwater technologies have been found to be effective practices for removing a diverse range of emerging pollutants including microplastics (Smyth et al., 2021) and 6PPD-Quinone (Rodgers et al., 2023). In rural lands, riparian buffers can reduce the concentration of pathogens like *Escherichia coli* by keeping livestock out of the waterways and passively filtering overland flow during wet weather (Lim et al., 2022).

Exploitation of freshwater through damming can also incur changes in water quality (Ellis and Jones, 2013; Winton et al., 2019). For example, dams are known to release cooler deeper water, often releasing hypoxic water downstream, while also altering thermal regimes (Winton et al., 2019). Hypoxic conditions were recorded for as far as 150 km below the Bakun Dam in Malayasia (Wera et al., 2019). However, through the implementation of appropriate e-flows, dissolved oxygen availability improved (Bednařík et al., 2017). Additionally, nutrients are often trapped behind dams, particularly phosphorus, causing oligotrophication within downstream habitats (Winton et al., 2019). For example, in the floodplains of the São Francisco River of Brazil, differential regulation of hydrodynamics caused significant changes in nutrient availability, thereby affecting fish biodiversity (Nestler et al., 2012). In the Lower Velhas River of Brazil no reservoirs are present; this river exhibits a normal flood pulse, which allows for nutrients to be deposited downstream (Nestler et al., 2012). As such, fish biodiversity is seen to be highest in this reach, whereas in the Lower São Francisco River, where water flow is heavily regulated due to eight upstream dams, fish biodiversity was shown to be severely decreased. This is thought to be due to material being deposited within the reservoir, resulting in poor water quality downstream (Nestler et al., 2012). As a result of this nutrient loading, eutrophication is also common within these reservoirs (Winton et al., 2019). Once again, proper use of e-flows has been shown to prevent cyanobacteria blooms (Chícharo et al., 2006), which suggest ecohydraulics could be a useful tool to prevent eutrophication.

Analytical tools and models of the hydraulic processes occurring within our aquatic environments are critical to understanding the mixing, dispersion and fate of pollutants. For example, mixing in a straight channel flow is dominated by turbulent diffusion, but the mixing of a point source effluent in a river is accelerated by helical secondary circulation patterns in the meandering river flow. Recent work has characterized this mixing process by utilizing field measurements (Pilechi et al., 2015, 2016), laboratory physical models (Schreiner et al., 2018), and highly resolved experiments and numerical models (Wang et al., 2022) that can identify the turbulent interactions between vortices in the point source effluent and the three-dimensional river bend flow. In practice, effluent concentration regulations are often based on dilution requirements, which depend on prediction of effluent mixing at scales of interest. Calculation of the spatiotemporal distribution of the effluent concentration utilizes the unsteady advection-diffusion equation with assumed mixing coefficients (Fischer et al., 1979; Rutherford, 1994). For example, Rehmann et al. (2021) recently used this approach to predict the spatiotemporal distribution of fire retardants in a stream network to assess exposure of aquatic species. The mixing coefficients can also be estimated by fitting to sampled observations of the velocity and concentration fields (e.g., Pilechi et al., 2016). Field measurements usually employ an acoustic Doppler current profiler (aDcp) for the velocity field, and effluent concentrations from either direct water sampling, dye concentration tracing, or use of a conductivity-temperature-depth (CTD) sonde to measure water density as a proxy for concentration (e.g., Pilechi et al., 2015). However, the resulting mixing coefficients integrate molecular and turbulent mixing over spatiotemporal scales dictated by the measurements. In contrast, experimental methods and numerical modelling now enable elucidation of mixing at the scale of individual large eddies (Schreiner et al. in review). Laboratory techniques include Particle Image Velocimetry (PIV) for the velocity field and Laser Induced Fluorescence (LIF) for the concentration field, while numerical approaches include Direct Numerical Simulation (DNS) and Large Eddy Simulation (LES), the latter of which is increasingly applied at field scale. The application of these tools to laboratory- and field-based studies demonstrate how ecohydraulics as a discipline is well positioned to develop solutions to mitigate and improve water quality to support aquatic life through the creation and restoration of natural flow pathways and water balances.

4. Action 3: Protect and restore critical habitats

Anthropogenic activities have severely modified freshwater ecosystems leading to habitat loss, fragmentation, and degradation, which in turn led to declines in biodiversity, with freshwater species being disproportionately affected (Dudgeon et al., 2006; Reid et al., 2019; Albert et al., 2021). Habitat protection has been a dominant strategy for conservation of biodiversity and involves minimizing or eliminating human disturbances from specified areas (see Piczak et al., 2023). Ecohydraulics has an important role to play, particularly in the protection of freshwater ecosystems given the inherent need of water for all organisms including humans (Krauze and Wagner, 2008). Across the globe, freshwater ecosystems have been subjected to intensive water withdrawals (e.g., for agriculture, domestic use, or industry; Ritchie and Roser, 2018), leading to water scarcities. These scarcities will likely be exacerbated by climate change in many regions, for example, in scenarios with reduced river discharge (from climate change and water withdrawals), as much as 75 % of the local fish diversity could become extinct by 2070 (Xenopoulos et al., 2005). Ecohydraulics can contribute to the protection of freshwater habitats in the form of identifying essential properties of e-flows (as outlined above), which can reduce risk of water scarcity, decrease habitat fragmentation, improve water quality (e.g., by dilution of pollutants), and ensure sediment transport (Rolls et al., 2012). In Australia, after a series of droughts in the Murray-Darling Basin, the dedication of at least 2750 gallons per year of water entitlements was mandated to protect river flow and connectivity, vegetation, waterfowl and native fishes (Harwood et al., 2017).

Next, one of the pillars of ecohydraulics is the restoration and assessment of freshwater habitats and ecosystems, which is crucial for effective and sustainable restoration actions. Therefore, ecohydraulics plays an important role in the protection, restoration, and creation of habitats and in the reestablishment of ecosystem functions (Rosenfeld and Hatfield, 2006). Ultimately, ecohydraulics has also been founded on the basis of habitat modelling (Tonina and Jorde, 2013). There has been a long tradition of assessing habitats with models, such as the Physical

Habitat Simulation System (PHABSIM), which was developed in the 1970s (Bovee, 1982) and that is still widely used. It is time to go one step further than traditional habitat models that often only focus on three abiotic variables, i.e., shelter, (substrate, cover), velocity, and depth, and include additional variables such as temperature (Bartholow et al., 1993; Havis et al., 1993; Muñoz-Mas et al., 2016; Railsback et al., 2021), ice (Heggenes et al., 2017) and food consumption (Chapman et al. 1969; Dill et al., 1981; Gehrke, 1991; Bevelhimer, 1996; Garner et al., 1998; Giannico et al. 1999; Booker et al., 2004; Hansen et al. 2005; Hayes et al., 2007; Naman et al., 2019, 2020) in order to provide practitioners with promising tools for a more holistic understanding of habitat needs and ecosystem functioning. Ecohydraulics is core to doing that. Furthermore, the integration of fluvial geomorphology within ecohydraulics has become an important aspect of river restorations (Newson and Large, 2006). Fluvial geomorphology considers the interplay between hydraulic forces and sediments, both spatially and temporally, in order to understand the formation of a given river (Grabowski et al., 2014). As such, fluvial assessments have provided valuable criteria for restoring rivers to past conditions (Gilvear et al. 1999; Sear et al., 2009; Grabowski et al., 2014). Similarly, biogeomorphology, which considers the interactions between living vegetation and geological systems (Corenblit et al., 2007; Gurnell, 2014; Wolh et al., 2019; Corenblit et al., 2024; Gurnell et al. 2024), plays an important role in identifying important habitats, for example, riparian areas, which are integral in maintaining biodiversity and stability in watersheds. Consequently, the modelling of such interactions has been of interest to many researchers (Benjankar er al. 2011; Bertoldi et al., 2014; Van Oorsschot et al., 2016; Caponi et al., 2023), which can provide useful information on these critical habitats. Next, by adapting innovative remote sensing technologies and temperature network models (Isaak et al., 2017), ecohydraulics will have the capacity to upscale habitat assessments and restoration planification to the riverscape (Fausch et al., 2002; Torgersen et al., 2022; Glassic et al., 2024). However, using remote sensing technologies can often be costly due to the scale of the riverscape and often needs a large team of highly trained personnel to be conducted in a timely manner (Torgensen et al. 2022). In addition, the adaptation of mechanistic individual-based models (IBMs; Railsback et al., 2009) and integrated multi-species approaches that often results in a more holistic understanding of biodiversity functioning and habitat management (Geist, 2011). Rosenfeld et al. (2022) suggested stressor-response functions as a useful tool for assessing cumulative effects of the prioritization of recovery and restoration actions based on their anticipated benefit for the ecosystem response (Jarvis et al., 2024; MacPherson et al., 2024). Currently, a large proportion of restoration and habitat creation initiatives fail to effectively mitigate degradation and halt biodiversity loss (Geist and Hawkins, 2016; Strailey and Suski, 2022). Nevertheless, there are continuing efforts to improve and restore stream and river habitat structures. For example, the creation of artificial streams to return watershed connectivity, allowing fish migration and restoring spawning and nursery habitat (Jones et al., 2003; Scrimgeour et al., 2014). Boulders provide invaluable habitat to many riverine species (Golpira et al., 2022). However, to assess the long-term success of a restoration project, it is essential to conduct targeted, long-term monitoring of both the aquatic organisms and habitat. To provide guidance on rigorous evaluation and monitoring of restoration initiatives to demonstrate their effectiveness and guide future restoration effort, it will be an important task for ecohydraulics in upcoming years to develop standardised effectiveness monitoring protocols in an adaptive management framework (DFO, 2012; Taylor et al., 2019). In addition, highlighting the importance of habitat connectivity (e.g., ecological corridors, green and blue belt networks), the protection of ecologically significant areas, and developing new innovative strategies such as nature-based solutions (NBS; van Reese et al. 2023), will be of key interests to the field of ecohydraulics.

5. Action 4: Manage exploitation of freshwater species and riverine aggregates

Fishing of aquatic animals at first glance may seem to have little to do with ecohydraulics, yet it is often ecohydraulic principles that dictates how aquatic animals are distributed in space and time and hence where fisheries gear is typically deployed. Although fishers focus efforts on target species, bycatch can occur including in freshwaters (Raby et al., 2011). Ecohydraulics can be used to identify the key habitats of both target and non-target species (including imperiled species) thus revealing how fisheries can be prosecuted while attempting to avoid unwanted catch, as has been done for freshwater turtles (bycatch) and target fish species (Larocque et al., 2012). In another example, river dolphin encountered in gillnets in Bangladesh were routinely associated with deepwater habitats creating opportunities to reduce catch by deploying in shallower habitats (Dewhurst-Richman et al., 2020). However, sometimes spatial (or temporal) segregation is not possible such that it is necessary to design gear that is more selective. Ecohydraulics can be combined with aspects of organismal sensory physiology to reveal opportunities for deterring or avoiding unwanted catch. Admittedly, most examples come from the marine space (reviewed in Horodysky et al., 2022). For example, hydraulic properties of trawls have been studied to identify opportunities for reducing bycatch of non-target fishes (see Parsons et al., 2012), and various deterrents such as lights, scents, and noise have been used for sea turtles (Southwood et al., 2008) and marine mammals (Lucas and Berggren, 2023). Those same tools may hold promise in freshwater systems, but more research is needed. It may be possible to capitalise on decades of ecohydraulics research and tools related to fish guidance systems, both physical (–e.g., bar racks) and non-physical (e.g., sound) to design better fishing gear. The last obvious opportunity is to exploit ecohydraulics knowledge to identify ways of recovering organisms that are captured and released (for various reasons). For example, for coho salmon encountered by gill nets during their initiation of upriver spawning migration, fish that were functionally moribund could be recovered by placing them in a recovery box that pushed water over their gills (Buchanan et al., 2002). Those ideas have since been refined where slow speed swimming (not just artificial respiration) has been deemed to be useful for expediting recovery of fish exhausted in freshwater fishing gear (Milligan et al., 2000), although this method does not work for all fishes (Suski et al., 2007).

The extraction of sand and gravel from rivers for construction aggregate (especially for concrete) is widespread but its impacts are commonly overlooked. Removing sand and gravel from river channels destabilizes rivers, causing channels to incise (downcut) (Lamb et al., 2019; Hackney et al., 2020), resulting in loss of habitat for aquatic organisms (Padmalal et al., 2008; Padmalal and Maya, 2014; Bhattacharya et al., 2019), declines in alluvial water tables, and intrusion of saline waters in delta environments (Eslami et al., 2019). Sand is already becoming scarce in many river basins due to over-exploitation, and with rapid population growth and urbanization, the demand for aggregates (and the environmental impacts of their extraction) are increasing (Zhong et al., 2022). The effects ofextraction activities are widespread and extend beyond the immediate sites of mining, as channel incision propagates upstream and downstream of mining sites. For a sustainable management of these resources, several critical steps are needed. These include obtaining quantitative knowledge of volumes, rates and locations of extraction, and establishing protocols for long-term monitoring and open access global networks for data-sharing. Ultimately, to lessen the demand for riverine aggregates, solutions lie in identifying: (i) alternative sources; (ii) sustainable sources of sand which are naturally replenished or with low environmental impacts from extraction; and (iii) incentives to reuse in-stock material. Because aggregate is needed for urban development, in many regions there is strong political pressure to allow unrestrained aggregate mining. However, where strong governance is in place to manage such activities, it can be possible to regulate extraction to locations and rates that minimize impacts. In northern California, the Mad River supports important runs of salmon and trout (*Oncorhynchus tshawytscha, O. kisutch,* and *O. mykiss*), but it is also an important source of aggregate for the region. For the last three decades, mining has been managed based on scientific data: each year following the wet season, a team of five experts reviews changes in river bed elevation documented in annual surveys to estimate the volume of fresh deposition, along with results of biological surveys. In years with abundant gravel deposition ("recruitment"), more aggregate could be mined, while in years without new deposition, no extraction could be permitted (Klein et al., 2019). In summary, ecohydraulic knowledge can support management decisions and ensure that aggregate extraction is consistent with maintenance of aquatic life.

Management of sediment remains an important aspect of river restorations (Wohl et al., 2015), in particular fine sediment, which provides vital spawning habitat for many species. For example, the introduction of dams, but also dam removal and rehabilitation, can cause disturbances in sediment deposition (Stanley and Doyle, 2003; Katopodis and Aadland, 2006; Foley et al., 2017; Katopodis and Kemp, 2018). In the past, dams have been constructed for freshwater access and hydroelectricity, with little to no consideration for aquatic life (Katopodis and Aadland, 2006). As such, dams can interfere with the transport of sediment downstream, which can result in the perching of floodplains and riparian areas, flattening of the channel and energy slope, and blockage of inflowing tributaries, which ultimately smothers downstream habitat (Katopodis and Aadland, 2006; Nestler et al., 2012; Boavida et al. 2020). However, in recent years due increases in societal pressures, we are seeing shifts in priorities to include eco-friendly features such as fish passageways and enforcement of natural flows, resulting in older dames being rehabilitated, removed, and replaced. Unfortunately, even the simplest dam removal can cause disruption of sediment resulting in unwanted downstream accumulation and increases in turbidity, thereby destabilizing the habitat (Stanley and Doyle, 2003; Katopodis and Aadland, 2006; Foley et al., 2017). Nevertheless, dam rehabilitation and removal are thought to improve river habitat (Bednarek, 2001; Katopodis and Aadland, 2006). If a dam cannot be removed, flushing flows should be considered. Flushing flows consist of periodically increasing dam flow to mimic natural flood conditions (Kondolf and Wilcock, 1996). This allows for fine sediment to be transported and deposited downstream and in some cases has been shown to remove macrophytes (Kondolf and Wilcock, 1996; Batalla and Vericat, 2009). However, careful consideration of the applied flows should be taken, as it also has the potential to negatively disturb the downstream environment if flows are too high (Kondolf and Wilcock, 1996). Taken together, management should consider the downstream effects when applying and modifying dams and identify whether further human intervention is needed to mitigate these effects (Stanley and Doyle, 2003; Katopodis and Aadland, 2006; Foley et al., 2017; Katopodis and Kemp, 2018; Katopodis, 2022).

6. Action 5: Prevent and control non-native species invasions in freshwater habitats

The invasion of non-native aquatic flora and fauna has been identified as an important driver of biodiversity loss in freshwater habitats (Dudgeon et al., 2006; Tickner et al., 2020). Preventing the initial introduction of non-native species in novel environments is the most effective management action; however, due to the wide range of possible organisms (e.g., plants, algae, insects, mollusks, microbes, fish) which employ an array of movement vectors, complete containment can be challenging. While regulation can help to limit the opportunity for human-mediated transport, impediments to hydrologic connectivity are necessary to limit volitional spread of non-native species. Intentional fragmentation in rivers and streams (e.g., dams or other exclusion barriers) for control of non-native species is often in conflict with conservation goals to increase connectivity (Jones et al., 2021). Development of selective connectivity, whereby native species are provided passage while non-native species are contained, has recently been proposed as a solution to the connectivity conundrum (Zielinski et al., 2020). In cases where non-native introductions cannot be prevented, alternative control measures are required to limit or even reverse their impacts, often exploiting dispersal traits of the non-native species, which, in many cases, is inextricably linked to hydraulic characteristics of the environment (e.g., David, 2003). Ecohydraulics provides a scientific framework in which to explore dispersal pathways and factors that influence dispersal—whether it be from volitional transport or by movement of host species—for species that currently or already pose a risk to biodiversity, understand how non-native species impact freshwater ecosystems, and to develop tools to both prevent and control their proliferation in freshwater ecosystems.

Numerical models that combine hydrodynamic simulations of aquatic ecosystems with individual-based models characterizing the life history and movement of non-native organisms is a common approach to explore dispersal pathways and factors that influence dispersal. Understanding localized expansion of non-native organisms is necessary to inform decision-making and resource allocations (Hoyer et al., 2014). For example, Beletsky et al. (2017) demonstrated that advection by lake currents is an important dispersal mechanism for invasive Eurasian ruffe (*Gymnocephalus cernua*) and golden mussel (*Limnoperna fortunei*) larvae in the Laurentian Great Lakes, and found offshore dispersal through deballasting can lead to broader dispersal than from nearshore sources. Dispersal models are also useful in identifying suitability of new habitat for non-native organisms. The FluEgg model is one such approach that combines 2-D hydraulic modeling with corrections for turbulent diffusion to simulate the downstream drift of eggs of invasive carp species (*Hypophthalmichthys* spp.) (Garcia et al., 2015). The principles of hydro-geomorphic processes have also been used to quantify the impact of invasive organisms on their environment. Harvey et al. (2019) created a conceptual model on how non-native animals that burrow into riverbanks can alter geotechnical, hydrological, and hydraulic processes at riverbanks through increased turbulence and sediment entrainment, alter flow resistance, and ultimately increase bank instability. In the case of non-native vegetation, Van Oorschot et al. (2017) found patterns of local and large-scale effects of non-native plant invasions are complicated by bio-geomorphological feedback mechanisms that can lead to impacts of hydro-morphodynamics that can be both beneficial and detrimental to native vegetation. Finally, ecohydraulic principles have led to the development of selective control strategies for non-native fish and plants. Tsubaki et al. (2024) developed a new biomass-flux assessment technique that showed critically timed flushing flows at a dam led to both decreases in non-native vegetation and increases in native vegetation. New approaches to selective fish passage (e.g., simultaneous passage of native fish while blocking non-native fish) have also suggested sorting mechanisms that exploit or overcome attributes of fish (e.g., morphology, swimming ability, behavioral response to environmental cues like turbulence or sound) (Noatch and Suski, 2012; Silva et al., 2018; Rahel and McLaughlin, 2018; Zielinski et al., 2020; Piczak et al., 2023; Santos et al., 2024; Romão et al., 2025). For example, vertical-slot-trap-and-sort fishways have been specifically designed to create a physical barrier for migrating spawning sea lamprey in the Laurentian Great Lakes (Pratt et al., 2009). Nevertheless, there remains a risk to entrap native migrating fishes within these passageways. However, through small modifications of these fishways, Pratt et al., (2009) showed upwards of a 30 % improvement in native fish passage, largely through increasing trap volume and optimizing funnel characteristics. As such, it has been demonstrated that setting low turbulent flow within the entrapment route, whilst having high flow in the upstream route, can increase effectiveness of trapping sea lamprey (Lewandoski et al., 2021).

Taken together, this suggests that exploiting ecohydraulics to target unique differences between native and non-native species can make selective fish passageways an effective barrier to reduce the latter.

7. Action 6: Safeguard and restore freshwater connectivity

Connectivity in freshwater systems includes longitudinal, lateral, and vertical elements, all of which have been impacted (i.e., fragmented) as a result of human activities and infrastructure including the construction of water control structures such as dams, channelization and levees, as well as water abstraction (reviewed in Thieme et al. In Press). Ecohydraulics has the potential to help safeguard and restore freshwater connectivity in several ways. With respect to safeguarding connectivity, ecohydraulics can be used to identify the extent to which different structures or activities represent barriers to connectivity, thus informing future development activities (McRae et al., 2012). For effective application of ecohydraulics in improving connectivity, plans will likely need to be enacted upon at a large (e.g., basin-wide) scale and may require the prioritization of actions. As such, river barrier prioritization tools have been developed (i.e., National Aquatic Barrier Inventory & Prioritization tool, https://aquaticbarriers.org/; Aquatic Barrier Prioritization; Maine Aquatic Barrier Prioritization tool, https://maps.coastalresilience.org/maine/#) Defining the fundamental needs for organisms that move longitudinally and laterally provides essential information to those that regulate human activities. For example, knowledge of the extent of longitudinal migrations for fish directly informs dam siting decisions as well as the need for fish passage (Twardek et al., 2022). Riparian fragmentation is often mitigated by the presence of nearshore/riparian vegetation which can be enhanced by requiring flows that enable the transfer of sediment (Poeppl et al., 2012) and propagules (Stevaux et al., 2013), so ecohydraulics can be used to identify optimal flows that enable lateral connectivity. Identifying minimal flows can ensure that development activities do not impede connectivity. Vertical connectivity protection can be informed by identifying minimum inputs and ensuring that collective water withdrawals do not impede fluvial processes necessary for aquatic life (Boano et al., 2014).

When connectivity has been impeded, ecohydraulics is well positioned to inform the restoration of this process. The most obvious example is in the context of upstream fish passage where the design of fishways (from attraction to passage) can (and should) be informed by ecohydraulic studies. For example, Marriner et al. (2014) revealed that so-called “resting pools” in fishways were actually areas of confusion that increased energy expenditure. Goodwin et al. (2014) linked sophisticated fish tracking data (from acoustic telemetry) with high resolution hydraulic data to understand how individual fish interacted with flow fields to inform upstream passage options. Swimming performance studies form the basis to inform hydraulic design for fish passages effective for multiple species (Katopodis et al., 2019). Tools have been developed based on a large fish swimming performance database (Katopodis and Gervais, 2016) and are used to provide guidance in designing fishways (SPOT https://www.fishprotectiontools.ca/). Fish passage technology for upstream and downstream migrating species has a long history that can inform retrofit or new installations (Katopodis and Williams, 2012). More recent studies have emphasized water velocity gradients and turbulence characteristics, especially for downstream fish passage. For example, comprehensive hydrodynamic studies on velocity gradients and turbulence characteristics that impact fish movements provide insights for more effective guidance and passage through safer routes, such as spillways (Aleyasin et al., 2025) or bar racks and bypasses (Fang et al., 2024) for downstream migrants. Ecohydraulics is also relevant to downstream passage where there is a need to provide aquatic life with safe routes to pass through harmful structures such as spillways and turbines (Brown et al., 2014). Ecohydraulic knowledge related to fish-turbine interactions can be used to design “fish friendly” turbines (Koukouvinis and Anagnostopoulos, 2023). Recent innovations include the testing of turbines with slanted and blunt leading edges (Amaral et al., 2020), novel propeller-type turbines (Watson et al., 2023), and linking behaviour and turbine configuration to identify “fish friendly” characteristics (Vowles et al., 2014). In addition, it is possible to behaviourally guide fish away from potentially dangerous areas towards safe passage using both physical and non-physical approaches (Noatch and Suski, 2012). For example, louvers designed with collaboration of ecologists and engineers are now widely used to guide salmonids (Scruton et al., 2002b), although struggles remain with guiding some other organisms such as sturgeon (Cooke et al., 2020). Screens can be used to reduce potential for fish entrainment but this also requires ecohydraulic knowledge to ensure that impingement is minimized (Russon et al., 2010). In fact, successful fish screen applications have been implemented at some hydroelectric plants (Nyqvist et al., 2018; Calles et al., 2021), which has promoted expansion for their use at larger facilities.

Ecohydraulic studies can also inform the development of channelization schemes that are being re-thought to re-establish connectivity. For example, in urban systems where watercourses have been channelized, recent research has been used to identify opportunities for creating hydraulic conditions that reduce physical damage (e.g., erosion) and benefit aquatic life (Anim et al., 2019) including through use of high flows to achieve cyclic floodplain rejuvenation (Geerling et al., 2013). Due to water abstraction and other human activities, vertical connectivity can also be impacted, but ecohydraulics can inform hyporheic reconnection (Boulton, 2007).

8. Ecohydraulics and the implementation of the emergency recovery plan

As outlined above, there are many ways that ecohydraulics has the potential to contribute to realizing the Emergency Recovery Plan for freshwater biodiversity spanning all six of the plan actions (Tickner et al., 2020). Yet, there are inherent challenges with doing so. The first is ensuring that the ecohydraulics community is aware of the freshwater biodiversity crisis which has largely gone unnoticed (Harrison et al., 2018). However, of equal importance is ensuring that the ecohydraulics community engages in a meaningful way with science to support recovery of freshwater biodiversity. As such, taking advantage of synergistic opportunities when various actions plans are involved may offer insightful ecohydraulic contributions and lead to more holistic, effective and balanced mitigation measures (Katopodis, 2022). Papers like ours are active attempts to raise such awareness but there is certainly more scope and space for our community to come together and share experiences (e.g., through workshops and symposia) on this topic. However, such efforts need to extend more broadly to decision makers (including politicians) and diverse publics to ensure that they are aware of the state of freshwater biodiversity and are committed to making the necessary science-based investments in conservation and have the political will to do so. Even when science exists that can inform decisions, for various complex reasons, the science may be ignored (Cook et al., 2013). Implementation requires not just generating new knowledge and solutions but applying them, and doing so through an adaptive management approach to enable more learning and refinement (see Bett et al. (2022) for an example of an adaptive management approach to improving fish passage at a dam in British Columbia). The ecohydraulics community could also do a better job with telling stories about its successes in this realm while simultaneously being candid about its failures (to enable failing forward; Catalano et al., 2019). To be clear, the role of scientists should first and foremost be generating new knowledge, but they also play a role in supporting the decision-making enterprise by ensuring that decision makers have access to said knowledge and by providing science advice when asked to do so.

This paper represents the first synthesis on the topic but there are certainly individuals and organizations that have been applying ecohydraulics to freshwater conservation for decades. Some of the earliest

Table 1
Ecohydraulic tools relevant to the Emergency Recovery Plan for Freshwater Biodiversity. Relevant actions are numbered as follows: (1) Accelerate implementation of environmental flows; (2) Improve water quality to sustain aquatic life; (3) Protect and restore critical habitats; (4) Manage exploitation of freshwater species and riverine aggregates; (5) Prevent and control non-native species invasions in freshwater habitats; 6) Safeguard and restore freshwater connectivity.

Tool	Examples	Relevant Action	Key References
Biotelemetry (e.g., Radio and Acoustic Telemetry, Passive Integrated Transponders) and Biologgers (e.g., Archival Loggers) Devices	- Assessing animal-environment interactions to identify fine space habitat use and responses to hydraulic conditions and inform modeling - Evaluating connectivity for mobile animals - Assessing response to behavioral guidance strategies - Validating flow-ecology relationships - Quantifying animal survival through various water infrastructure (e.g., turbines)	1,2,3,4,5,6	Scruton et al., (2002a); Struthers et al., (2017); Taylor et al., (2017); Enders et al., (2019); Rudolfsen et al., (2021); Renardy et al., (2023)
Sensors on Biologgers or Telemetry Tags (e.g., Temperature, Oxygen, Pressure, Acceleration, Heart Rate)	- Assessing animal-environment interactions to identify fine space habitat use and responses to hydraulic conditions - Evaluating connectivity for mobile animals - Assessing response to behavioral guidance strategies (e.g., thermal refuges) - Assessing energy use relative to different habitats, flow conditions, and infrastructure - Validating flow-ecology relationships - Quantifying animal survival through various water infrastructure (e.g., turbines)	1,2,3,4,5,6	Burnett et al., (2014); Silva et al., (2015)
Artificial Intelligence	- Developing new fish (and other aquatic animal) habitat models based on meta-analyses - Streamlining and enhancing studies on drift of riverine organisms to assess e-flows, hydropeaking, water quality and connectivity - Enabling image analysis for surface velocimetry - Developing predictive models of animal movement	1,2,3,4,5,6	Hu et al., (2019); Olivetti et al., (2021); Ansari et al., (2023).
Aerial Drones and Associated Imagery	- Advances in habitat classification and mapping - Characterizing bathymetry, river depth, and substrate conditions - Conducting surface velocimetry measurements	1,3,4,6	Woodget et al., (2017); Sundt et al., (2021); Consoli et al., (2022); Ansari et al., (2023); Glowa et al., (2023)
Electronic Sensors for Quantification of Physical and Hydraulic Stressors (e.g. Sensor Fish)	- Assessing hazards for downstream passage of fish around hydraulic structures.	6	Deng et al., (2014); Pauwels et al., (2022)
Flow Sensors (e.g., Particle Image Velocimetry, ADCPs)	- Augmenting flow data in sparsely monitored river systems - Mapping three-dimensional flow fields	1,3,4,5,6	Pilechi et al., (2015); Parsapour-Moghaddam et al., (2019); Alongi (2022); Ansari et al., (2023)
Computational Fluid Dynamics Models	- Characterizing hydraulic patterns that enable safe fish passage - Characterizing the dispersal patterns of aquatic eggs and larvae - Advancing morphodynamic habitat modelling	1,3,5,6	Garcia et al., (2015); Quaresma et al., (2018); Enders et al., (2019); Parsapour-Moghaddam et al., (2019); Sanz-Ronda et al., (2021); Fuentes-Pérez et al., (2022)
Swim Tunnels/Respirometry	- Evaluating impacts of water quality on fish - Quantifying the swimming capacity of fish and other organisms (e.g., turtles) - Quantifying effects of water temperature on animal energetics and performance	2,3,5,6	Santos et al., (2012); Oligny-Hébert et al., (2015); Svendsen et al., (2016); Egger et al., (2020); Beauregard et al., (2013)
Underwater Cameras and Shore-Based Cameras	- Assessing fish behaviour - Evaluating fish passage performance - Evaluating fish stranding	3,5,6	Sanz-Ronda et al., (2021); Glowa et al., (2022); Boavida et al., (2023)
Hydraulic Flumes and Associated Laboratory Approaches	- Determining the fish movement responses in relation to hydraulic conditions - Testing the effectiveness of innovative upstream and downstream fish passage designs - Quantifying the effects of hydraulic and physical stressors on fish - Elucidating mixing processes	1, 3, 5, 6	Enders et al., (2009); Wilkes et al., (2017); Schreiner et al., (2018); Costa et al., (2019); Moreira et al., (2020); Baladrón et al., (2021); Kastinger et al., (2023); Kerr et al., (2023); Leite et al., (2024)
Agent-Based Modelling	- Understanding or predicting animal movement responses to environmental conditions (flow and water quality) - Predicting dispersal of aquatic vegetation	1,2,3,4,5,6	Goodwin et al., (2014); Beletsky et al., (2017); Van Oorschot et al., (2017)

work was on topics such as fish passage (reviewed in Clay, 1961) and fish instream flow needs (reviewed in Bovee, 1982). As we have documented here, ecohydraulics is relevant to a wide range of issues, spanning taxa beyond fish. It is also critical to think about how climate change should be incorporated into ecohydraulics research so as to future-proof any management actions (Lynch et al. In Press). For example, implementation of river restoration (Palmer et al., 2005; Katopodis and Kemp, 2018) needs to be done not just in the context of hydrology today but what it will look like on longer horizons so that investments today have longevity in achieving conservation gains. In that context, it is important to consider morphodynamics, thermal regimes and ice-dynamics (Brown et al., 2011). Ecohydraulics is well positioned to be able to model and predict the effectiveness of various interventions in different climate change scenarios (Brewer et al., 2018), which will be foundational to future-proofing the six emergency recovery plan actions.

9. Conclusions

Ecohydraulics is at the nexus of ecology and hydraulics and is rapidly evolving as a discipline. Across the globe, freshwater biodiversity is in a crisis state, and we contend that ecohydraulics has a key role to play relevant to the six actions of the Emergency Recovery Plan for freshwater biodiversity. First, within the action to accelerate the implementation of environmental flows, we demonstrated how ecohydraulics is instrumental in the development, improvement, implementation, and evaluation of environmental flows. This can aid in the mitigation of stressors such as water abstraction, change in hydrological regime, and habitat fragmentation, which adversely impacts many freshwater species. Next, for improved water quality, ecohydraulics can be used to remediate sources of pollution through processes such as infiltration, ultimately contributing to the mitigation of habitat degradation. Third, under the protection and restoration of critical habitats, ecohydraulics can aid in the protection of freshwater habitats through the maintenance of minimal flows while it can guide restoration via the habitat needs of one or multiple species of interest. Fourth, for managing overexploitation of freshwater species and aggregates, ecohydraulics can identify the distribution of species in efforts to decrease bycatch and could decrease reliance on riverine aggregates. Fifth, for the prevention and control of non-native species, ecohydraulics has been shown to play an important role mitigating the connectivity conundrum and aid in the design of mitigate methods such as intentional fragmentation. Sixth, and last, in terms of safeguarding and restoring freshwater connectivity, ecohydraulics can protect (e.g., identify potential barriers) and mitigate (e.g., guide passage designs) connectivity issues. For all six actions, modern tools in ecohydraulics (see Table 1; or that operate in allied disciplines) like remote sensing, artificial intelligence, and other existing or future innovative methods and models will support further development. In particular, there is a need models and tools that accelerate the use and outcome of ecohydraulics studies. Yet ecohydraulics still has much to do in terms of bridging the gap between theory and practice which will close the so-called “implementation gap” (Cook et al., 2013). Doing so means generating knowledge that is relevant to decision makers which can be achieved through partnership projects that embrace co-production (see Cooke et al., 2021 for an aquatic perspective on co-production). Although there may be challenges associated with implementation, it is our hope that this paper raises the awareness of this promising discipline, which could contribute to the conservation and restoration of freshwater ecosystems and freshwater biodiversity.

CRediT authorship contribution statement

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Statement on the use of artificial intelligence tools

We proudly state that no AI tools were used in the development or writing of this manuscript.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: Cooke and several co-authors are on the editorial advisory board of the journal Water Biology and Security but were not involved in handling this manuscript.

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