ADVANCING ECOHYDRAULICS AND ECOHYDROLOGY BY CLARIFYING THE ROLE OF THEIR COMPONENT INTERDISCIPLINES.

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ADVANCING ECOHYDRAULICS AND ECOHYDROLOGY BY CLARIFYING THE ROLE OF THEIR COMPONENT INTERDISCIPLINES.

Increasing awareness of the complexity of river ecosystems has led to the emergence of integrative disciplines that combine topics in river physical and ecological processes, exemplified by the disciplines of ecohydrology, hydroecology and ecohydraulics. However, the names of these disciplines are often referred to interchangeably without attention paid to their meaning. This ambiguity impairs the efficient development and widespread promotion of these fields of study and their applications. To address this issue, we strive to clarify the definitions and contributions of the different disciplines. This is done by exploring their interrelationships and providing a reference for the integration of disciplines in these evolving fields. Finally, we advocate for ecohydrology and ecohydraulics to be considered complementary, and not duplicative, disciplines within river science. We further argue that awareness of their similarities and differences is important to address key issues in river science and to ensure ecohydraulics finds its positioning with respect to other disciplines and current and emerging societal and scientific challenges, such as climate change.

Keywords**:** ecohydraulics; ecohydrology; river; scale; e- flows; multidisciplinary.

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1. Introduction

Concurrent awareness of the complexity of riverine ecosystems and of their fragility to human pressures has contributed to the development and establishment of scientific disciplines to increase the understanding of these systems and contribute to their sustainable management and conservation. As a result, ecohydrology, hydroecology, ecohydraulics have gained momentum and are now well-established disciplines among scientists and practitioners, as evidenced by the increasing number of publications, conferences, and jobs labelled under these disciplines (Kemp et al. 2000; Rodriguez-Iturbe 2000; Petts 2007; Wood et al. 2008; Nestler et al. 2016b; Thoms et al. 2016). Riverine ecosystems are complex in that they include interlinked compartments aside from the river channel itself, e.g. riparian zones and adjacent floodplains and wetlands (Harris et al. 2000; Thorp et al. 2006), with water flow being the linking agent. Since the early 2000s, approaches to the study of river ecosystems have evolved, in particular due to the integration of the principles of landscape ecology, leading to the notion of riverscapes (Fausch et al. 2002; Wiens 2002; Allan 2004). Wiens (2002), in particular, relates that rivers can be considered in 3 ways from a landscape perspective: 1) as elements of a landscape separated by river banks; 2) as elements linked to their surroundings by boundary dynamics governed by water flow and associated fluxes; and 3) as heterogenous systems themselves, with patterns of mesohabitat assemblages and instream features governed by flow and local dynamic processes. As the transition zone between the river channel and the floodplain, riparian zones constitute the link between riverine and terrestrial ecosystems via fluxes of material, energy and movement of mobile biota. Riparian zones are an essential component of riverine ecosystems (Dufour et al. 2019): they influence hydromorphology, as they regulate fine sediment entry in streams and

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rivers, as well as water quality through nutrient and pesticide inflow regulation (Hill 1996; Nayman & Décamp 1997). Riparian zones also contribute to ecosystem engineering through resistance to flow and sediment accretion, resulting in a strong influence on rivers at the landscape scale (Gurnell & Petts 2006). Their structure is also highly dependent on flow regime (Goodson et al. 2001). Floodplains and adjacent wetlands regulate sediment, water and solute transport between the river channel and terrestrial ecosystems, depending on flooding patterns (Junk et al. 1989; Niswander & Mitsch 1995; Burt 1997). They play an important role for river fish life cycle by providing suitable spawning grounds and nursery areas with abundant food sources for larvae and juveniles (King et al. 2003; Stoffels et al. 2014). It is the connectivity and functioning of these different compartments together that ensure the health and resilience of riverine ecosystems (Bunn et al. 2001; Elosegi et al. 2010). Critical also to the successful management of these systems is the comprehension that processes governing river ecosystem functioning and organism life history operate and interact across multiple spatial and temporal scales (Fausch et al. 2002). For example, fish local habitat choices and cues to movements are influenced by local hydraulic conditions while they also move to other suitable patches over long distances. Moreover, most instream processes and conditions – such as water quality, sediment conditions or local hydraulics- are influenced by processes and land use occurring at a much broader scale, such as the catchment scale (Allan 2004; Gosselin 2015). An understanding and integration of these different scales is needed to grasp the complex and diverse nature of river systems (see Fausch et al. 2002, Figure 5). Moreover, the variety of processes involved in river functioning means that understanding and managing these ecosystems require interdisciplinary approaches, by which we mean the involvement of multiple academic disciplines.

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A variety of disciplines, both in natural science and engineering, focus on different aspects, functions and compartments of riverine ecosystems (Table 1). Fluvial geormophology investigates linkages between river channels forms and processes over a variety of spatial and time scales (Charlton 2007). Hydromorphology is defined as the study of the physical character and water content of water bodies, namely “subfield of hydrology that deals with structure and evolution of Earth’s water resources…deals with the dynamic morphology of water resource systems caused by both natural and anthropogenic phenomena” (Vogel 2011). The definition of hydromorphology implies a study over large scales whereas, in practice, hydromorphological characterization of rivers takes place over multiple scales and using a variety of indicators and methods relevant to ecohydraulics and ecohydrology (Hauer et al. 2009; Boon et al. 2010; Forseth and Harby 2013) and is related to both disciplines. Hydrobiology is another example. It is considered a subdiscipline of ecology and includes, among others, taxonomy and physiology. Studies in this field focus on limnology and ecology of lotic and lentic systems. As such it is a synonym for Freshwater Biology (Schwoerbel 2016). The term ’biology’ implies that the main focus is on organisms. In the context of fluvial ecosystems, ecomorphology focuses on the role of geomorphology as a template for ecological processes and functions (Fisher et al. 2007).

River Science is an umbrella term that encompasses a whole array of disciplines and topics of investigation (e.g. limnology, geormophology, biology) and that conveys the important idea of continuum and interactions of ideas amongst disciplines from abiotic to biotic focus in the same way as compartments of a river ecosystem interact with each other (Gilvear et al. 2016). Processes, may they be geormorphological, biological or hydrological, interact in a dynamic way along the river corridor as well

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as in vertical and lateral dimensions and across multiple temporal scales as per the Riverine Ecosystem Synthesis (Thorp et al. 2006). The name “river science” is rather self-explanatory and its focus easily conveyed to not only scientists but also to the larger audience outside of academia and science.

Ecohydraulics, ecohydrology and hydroecology all incorporate the topics of flow, flow-related processes and links between flow and ecology and, in that sense, can appear similar. Although precise definitions of ecohydraulics, ecohydrology and hydroecology have been proposed at an early stage (e.g. Kundzewicz 2002; Hannah et al. 2004; Lancaster and Downes 2010; Maddock et al. 2013), confusion remains with respect to their focus, as the disciplines are in constant evolution. One cause for this can be found in the multidisciplinary nature of these relatively new disciplines, meaning they are characterized by the coupling of ecology with other academic disciplines for the purpose of investigations. Other causes lie in the interdisciplinarity of river flow-related studies (i.e. they involve several academic and scientific disciplines), intercontinental differences, and differences in how these disciplines are viewed and related to individuals’ educational and professional background (Hannah et al. 2004). For example, from the published literature, the difference in focus effectively separates ecohydraulic studies from those in ecohydrology and hydroecology. In principle, the latter two disciplines focus on hydrology and water flow, often at larger scales, (e.g. catchment scale), and are traditionally more applied to assess sediment transport or vegetation succession in relation to flow (Zalewski 2002; Wilcox 2010). Hydrology seeks to describe, explain and predict the occurrence, circulation, distribution and properties of water and its relationship with terrestrial and

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atmospheric environments (Thompson 2017). This definition conveys an already strong, integrated multidisciplinary aspect within the discipline itself.

On the other hand, ecohydraulics focuses on hydraulics, i.e. a wide range of instream processes that are dependent on flow, but at smaller scales than hydrology. Hydraulics fundamentally focuses on practical applications in relation to water (and other fluids) in motion and its energy-related properties (Pagliara & Palermo 2017). Thus, the disciplines of environmental hydraulics and environmental fluid mechanics contribute to ecohydraulics. Indeed, environmental hydraulics is described as the "domain of research and investigation of the physical, chemical and biological attributes of flowing water, with the objective of protecting and enhancing the quality of the environment" (Rowinski 2007). Environmental hydraulics is based on hydraulics and in an environmental continuum (Singh & Hager 1996). Environmental fluid mechanics, on the other hand, is defined as the scientific study of naturally occurring flows of air and water that affect the environmental quality of those fluids. Of particular importance in environmental fluid mechanics, when considering flowing water, is turbulence (e.g. Rubin & Atkinson 2001). Ecohydraulics was initially considered a subdiscipline of ecohydrology. In its infancy, it mainly focused on modelling of physical habitat for aquatic biota, particularly in the context of the effect of instream structures such as dams, and on design and performance of fish passage, predominantly applied to salmonids because of their ecological and economic value (Maddock et al. 2013; Haro et al. 2015; Booker 2016; Benjankar et al. 2018), thus addressing environmental issues using (hydraulic) engineering tools. This applied nature of ecohydraulics can give it an engineering flavor.

However, when considering ecohydrology and ecoydraulics, the term 'eco' remains somewhat vague and is used as an umbrella to cover a broad range of

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ecological and biological aspects. This is inherent to the definition of ecology itself as the branch of biology which investigates the interactions between organisms and their environment (e.g. Allan and Castillo 2007). As the common denominator to ecohydraulics, ecohydrology and hydroecology, ecology is itself characterized and governed by a strong set of guiding principles. The goal here is not to detail the guiding principles of ecology but rather to provide a short reminder of its basic definition and to put it in the context of the present discussion. Ecology is defined as the study of biodiversity and of the interactions between organisms and their environment, both biotic and abiotic (Begon et al. 2006). Ecology is deemed “fundamental” when seeking to advance the knowledge on particular systems, while “applied ecology” seeks to solve specific problems in terms of resource management or environmental impacts (Allen and Hoextra 2015; Courchamp et al. 2015). Hence, ecohydrology reflects the hydrology relevant to ecology and ecohydraulics the hydraulics relevant to ecology. Hydroecology can be viewed as the part of ecology that takes place in water, hence a synonym for aquatic ecology (“hydro” is Greek for water).

Aside from the differences in definitions, there is disagreement on the appropriate scientific paradigm for each of these disciplines (Nestler et al. 2016a). This is also linked to the emergence of new sub-terminology to accommodate the development of other interdisciplinary approaches (e.g. hydromorphology, ecogeomorphology or ecohydromorphology - Thoms & Parsons 2002; Vogel 2011) situated at the interface of more traditional disciplines. Since the emergence of these disciplines, definitions and approaches were provided to establish them as scientific fields in their own rights. The result of these efforts is found in the growing number of

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publications (see overview in Hannah et al. 2004 and in Casas-Mulet et al. 2016), published books (Acreman 2001; Wood et al. 2008; Maddock et al. 2013), creation of journals (e.g. *Journal of Ecohydraulics*, *Ecohydrology, Ecohydrology & Hydrobiology*) and organization of conferences (e.g. *International Symposium of Ecohydraulics, HydroEco, International Society for River Science conferences, International River Symposiums, among others*).

Perception of ecohydraulics, ecohydrology and hydroecology by both practitioners and researchers familiar with these fields, and people outside of these fields displays an overall sense of confusion (Naiman et al. 2006; Wood et al. 2008; Rickwood et al. 2010). Some of the grounds for confusion include the separate disciplinary origins of ecohydrology and ecohydraulics (natural sciences versus engineering, respectively), the scope of the disciplines (incorporation of terrestrial ecosystems vs sole focus on aquatic ecosystems), and the scale of focus (catchment versus micro/mesoscale), the latter for which there is more agreement (Rice et al. 2010; Blanckaert et al. 2013; Zalewski 2015; Nestler et al. 2016b). As an example, Rice et al. (2010) found that the theme "ecohydraulics" appealed more to physical scientists than to biologists and ecologists. It is now paramount to promote and communicate these disciplines and their applications (e.g. watershed management, ecosystem conservation; E-flows) to funding agencies, stakeholders, and partners (in- and outside of academia). There is also a need to establish a strong foundation and guiding principles (Nestler et al. 2016a, 2016b) to further promote the integration of these disciplines and their future development.

Therefore, we believe it necessary to investigate the terminology and definitions for ecohydrology, ecohydraulics and hydroecology as each discipline seeks to formulate its own unique guiding principles. To do so, we, first, investigated

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and analyzed the similarities, overlaps and differences among ecohydrology, hydroecology and ecohydraulics regarding their use, focus and topic coverage. Second, we discuss the place and scope, the specificities, scale and respective fields of investigation for not only these disciplines, but also for other disciplines and subdisciplines, to achieve better understanding of the scientific and academic basis of river related investigations. Increased clarity in that respect will contribute to better study and management of aquatic ecosystems.

2. Back to basics: definitions of the disciplines, similarities and differences

2.1 Ecohydrology and Hydroecology: definitions and scope.

The definitions and scope of use of ecohydrology and hydroecology were already proposed by Wood et al. (2008b). Various definitions of ecohydrology have been provided since the early 2000, when discussion on this concept started (Nuttle 2002). From 'the study of the functional inter-relationships between hydrology and biota at the catchment scale as a new approach to achieving sustainable management of water' (Zalewski 2000) to 'the science of integrating to hydrological and biological processes over varied spatial and temporal scales' (Bonacci et al. 2009), ecohydrology has been defined as a new paradigm providing a holistic approach to water resources management.

Over the years, ecohydrology has incorporated topics such as land use change, terrestrial-aquatic linkages, trophic structures, biodiversity, ecosystem services and resilience to climate change to understand natural processes and achieve sustainability of aquatic ecosystems in a human-influenced landscape so as to encompass the complexity of riverine ecosystems and the interactions among their compartments, as

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defined in the introduction. Indeed, studies in ecohydrology incorporate the roles and functions of riparian zones, floodplains and adjacent wetlands and their influence, for example, on hydromorphology (e.g. Warren & Kraft 2003; Wawrzyniak et al. 2016), other instream processes such as water temperature dynamics (e.g. Sweeney and Newbold 2014; Ouellet et al. 2017) or ecological responses such as food web alterations (e.g. Kawagushi et al. 2003; Hladyz et al. 2011). This is evidenced, for example, by the diversity of articles published in the journal 'Ecohydrology' since the first issue in 2008.

In 2004, Hannah et al. suggested the use of the term hydroecology to refer to hydrology-ecology interactions on a broader sense, under which ecohydrology would be nested and would refer more specifically to plant-water interactions. They later established the theoretical fundaments of hydroecology upon which studies in this discipline should be based. They included, in particular, the need to take into account feedback mechanisms that exist as part of the interactions between hydrology and ecology, and the requirement to thoroughly understand the processes behind hydroecological linkages. Furthermore, they defined the subject scope to include all water related environments and biota, and the processes that operate in these environments over a range of spatial and temporal scales (Wood et al. 2008).

As a result, ecohydrology has evolved beyond the relatively basic concept of integration of hydrology and ecology to become a true interdisciplinary science. In addition, it is defined by UNESCO (2011) as an "integrative science focusing on the interactions between the hydrology and biota", which provides it with international recognition for water resource management and conservation. From a scientific

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research perspective, the broad range of themes and applications within ecohydrology and hydroecology is further exemplified by the variety of conferences and sessions that incorporate them (e.g. HydroEco conferences of 2013, 2015 and 2017; International Conference on Engineering and Ecohydrology for Fish Passage of 2014, 2015 and 2019; International Society for Ecological Modelling conference – ISEM- of 2015, 2017 and 2019; some sessions in the International Symposium of Ecohydraulics, and in conferences of the International Society for River Science, among others). More recent emphasis has been on the study of interfaces to achieve a better understanding of linkages among ecosystems (e.g. terrestrial, aquatic, groundwater, and coastal) and develop and promote more integrative management and conservation strategies (Krause et al. 2017; Danielaini et al. 2018).

Ecohydrology and hydroecology clearly emerged from multidisciplinary concepts and from the need to find solution-oriented methods for understanding and reducing anthropogenic impacts on aquatic ecosystems (Janauer 2000; Falkenmark et al. 2004; Harper et al. 2008). Although a clarified definition for each discipline was proposed, the two terms -hydroecology and ecohydrology- still appear to be used interchangeably today. Regional preferences and backgrounds, *i.e.* ecologists vs hydrologists, partly explain this, and the use of one or the other term often appears to reflect a personal preference of the author’s or speaker’s predominant field of study.

2.2 Ecohydraulics: definition and scope

The foundation of ecohydraulics lies at the interface between traditional river centered, natural science-related disciplines and engineering-related, applied disciplines to address challenges facing both hydraulics and flow-related processes which impact ecology in river systems (Lancaster and Downes 2010a). Ecohydraulics

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finds its fundament in the dynamic, flow regime-dependent nature of river systems, and, as such, incorporates hydraulic processes resulting from moving water and observed responses in terms of aquatic ecology and biology (Lancaster and Downes 2010a; Maddock et al. 2013; Lancaster 2019). It originated from assessment methods for aquatic habitats and, subsequently, the design of environmental flows (Morin et al. 2003; Mingelbier et al. 2008; Rice et al. 2010).

Although initially considered a subdiscipline of ecohydrology (Wood et al. 2007), the focus of ecohydraulics is, in fact, distinct. Ecohydraulics originates from a more applied science perspective, from the need to address environmental issues that solely ecological tools could not address, and, as a result, emphasizes more on multidisciplinary approaches to remediation measures in response to anthropogenic impacts such as: the design of efficient fish passage facilities (Katopodis and Williams 2012; Kemp 2012); implementation of environmental flows in response to water abstraction; flow regulation and hydropower (Tharme 2003); the development and use of modelling tools for the characterization of river processes and responses (Paraciewicz 2001; Bockelmann et al. 2004); and hydromorphological measures to restore habitat quality and quantity for biota (Maddock et al. 2013; Wheaton et al. 2017). Ecohydraulics focuses on instream processes using an applied perspective (Lancaster & Downes 2010) in contrast to ecohydrology. As such we can say that the focus of ecohydraulics is on the third characteristic of riverscapes, as expressed in Wiens (2002), i.e. rivers as internally heterogenous with a variety of habitats and instream features that vary in space and time. For example, ecohydraulic studies consider instream vegetation for its role as instream habitat engineers for fish and macroinvertebrates, for its influence on

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local flow hydraulics and sediment transport (Cotton et al. 2006; Sand-jensen 2008; Schnauder & Moggridge 2009; Janauer et al. 2013) or, in reverse, investigate how instream hydraulics influence sediment and plant propagule transport (Gurnell 2007; Pasternack et al. 2008). The diversity of topics relevant to ecohydraulics is further reflected in the programmes of the International Symposium for Ecohydraulics (ISE) since 1994 with an increase in both the number of sessions organized (3.5 factor increase) and the number of papers presented (10 factor increase) (Vaskinn et al. 1994; Leclerc et al. 1996; Hardy et al. 1999; King and Brown 2002; Garcia de Jalon et al. 2004; Jowett and Biggs 2007; Parra et al. 2009; Jee et al. 2010; Mader et al. 2012; Harby et al. 2014; Webb et al. 2016).

2.3 Ecohydraulics, ecohydrology and hydroecology: similarities and differences.

Scientific material with the tag “ecohydraulics” is nested predominantly under the categories “Water Resources”, “Environmental Sciences” and “Ecology” but also under engineering-related categories (civil, environmental, and, to a much lesser extent, mechanical) in Web of Knowledge (Figure 1). The latter can be explained partly by the applied nature of ecohydraulics and by the heavy reliance of hydraulics on calculus, in comparison to hydrology, as previously explained. This led to apprehension by experimental scientists towards some ecohydraulics studies and conclusions because they felt that relatively simple mathematic constructs (as used in Instream Flow Incremental Method - IFIM studies) trivialized ecological significance and reasoning (Lancaster and Downes 2010). This can also explain why the range of categories in which “ecohydraulics”- tagged documents are found is also narrower (23) than that for ecohydrology and hydroecology (33). Furthermore, the low number of items found under “ecohydraulics” (96) reflects the specificity of the discipline, its

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relative novelty and its strong "applied" component while the other disciplines present a more basic science flavor. As a result, ecohydrology is more diverse with 840 documents tagged with that keyword (106 for hydroecology) with a strong focus on geosciences and ecology (water resources management for hydroecology). In comparison, the search for documents tagged under "River Science" returned 12 579 items under more than 100 subject categories (many of which overlap those for ecohydraulics, hydroecology and ecohydrology), thus confirming the broadness of the discipline and its role as an umbrella term, as we described in the introduction.

The disciplinary bases from which ecohydraulics and ecohydrology have emerged differ significantly in focus, scope and scale. From these differences it is evident that their development and evolution as disciplines were not coordinated by their respective practitioners. Each evolved from separate traditions to address different applied questions of water resources management (and other uses). Typically, hydraulics practitioners make heavy use of calculus to implement conservation principles (of mass, energy, and momentum) at a cell-by-cell level of resolution based on the physical properties of solid boundaries and the dynamics of the fluid boundaries (i.e., inflows and outflows). Governing equations like the Navier-Stokes or St. Venant equations are often discretized (i.e., distributed) into cells or meshes, and characteristics of the flow field are then obtained by aggregating fluid behavior across the grid or mesh (Escauriaza et al. 2017). In contrast, hydrology makes heavy use of descriptive statistics to implement conservation principles at larger time and space scales (Thompson 2017). For example, the unit hydrograph principle uses observed data to develop rainfall-runoff relationships that can be used to estimate the volume and timing of water entering a river channel from its watershed (Dingman 2015). Then, kinematic wave routing describes the flattening and

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broadening of a flood wave (based on previously collected flooding data) as it moves downstream after a rainfall event to be used to estimate flood height and arrival time. Another difference lies in the basic units used for analysis. While in hydrology it is the transect and the primary variables of concern are stage and discharge, in hydraulics the basic unit of analysis is a cell or node within a cross section, grid and mesh.

The same differences between hydraulics and hydrology translate into ecohydraulics and ecohydrology when a coupling or linking code is used to convert hydraulic data or hydrologic data, respectively, into information useful for ecology (Figure 2). For example, two common ecohydraulic tools, those in the Physical Habitat Simulation (PHABSIM) system of the Instream Flow Incremental Method (IFIM; Bovee 1998) and the Eulerian-Lagrangian-Agent Method (ELAM, Goodwin et al. 2006) use cell or sub-cell level of information to determine habitat value (IFIM) or forecast fish movement (ELAM) respectively. In contrast, two common ecohydrologic tools, the Ecosystem Function Model (EFM, Dunn and Hickey 2003) and Indicators of Hydrologic Alteration (IHA; Richter et al. 1996; Mathews and Richter 2007) use transect information. The EFM relates stage-duration information to impact on vegetation dynamics and the IHA uses a series of statistical tools to characterize how river regulation or water withdrawals will alter the hydrology of a target river with the assumption that greater alteration has greater impacts on biodiversity and sustainability.

Nonetheless hydrology and hydraulics can overlap in theory and practice. For example, in a simple, uniform, u-shaped channel with little bottom sediment diversity

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the hydraulic analysis and hydrologic analyses will converge because each of the cells becomes a replicate of each other and therefore the channel can be represented as a single uniform cell. As a result, a hydraulic simulation of stage and discharge should closely approximate a hydrologic simulation of stage and discharge. However, more often than not, river channels are non-uniform, with diversity occurring over a variety of scales (micro-, meso-, reach scale) (Johnson et al. 1995; Thoms 2006; Hooke 2007; Gray et al. 2009).

The co-development of ecohydrology and ecohydraulics and their inter-relation are further examplified by the increasing co-organisation of sessions on both disciplines during ISE conferences. Evidently, session themes reflect both the development and relevance of particular topics with respect to current research and management issues, and, to some extent, the organisers' preference. Nevertheless, the evolution of the session themes since 1994 reflects also the strong linkages, and to a certain degree, some overlap in focus and scale, between ecohydrology and ecohydraulics (Vaskinn et al. 1994; Leclerc et al. 1996; Hardy et al. 1999; King and Brown 2002; Garcia de Jalon et al. 2004; Jowett and Biggs 2007; Parra et al. 2009; Jee et al. 2010; Mader et al. 2012; Harby et al. 2014; Webb et al. 2016). While, initially, the majority of the sessions focused on hydraulics and its applications to dam operations and fish passage (e.g. fish hydraulics habitat modelling, vegetation-channel hydraulics), the scope of the conference has evolved and broadened over the years to reflect not only the progress made in hydraulic modelling and the ever-growing possibilities of applying hydraulic modelling tools to environmental issues, but also the growing awareness of environmental linkages and their complexity in river systems, which required multi-disciplinary approaches. As a result, from purely process-orientated sessions, the conference has evolved to include broader – scale

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topics such as coastal-fluvial-estuarian interactions (e.g. Leclerc et al. 1996), water management (e.g. Jowett and Biggs 2007, Harby et al. 2014), aquatic ecological restoration (e.g. Jee et al. 2010; Harby et al. 2014), or Hydrology-Ecology (e.g. Webb et al. 2016). Ecohydrology related sessions have increased in importance over the years, and this can be viewed as symptomatic of the lack of establishing principles in ecohydraulics (Nestler et al. 2016b). While the sessions reflect the diversity of backgrounds of scientists and of studies carried out in these fields, they also reflect the lack of boundaries in practice between ecohydraulics and ecohydrology.

3. Integration of Ecohydraulics and Ecohydrology as a way forward.

The science of environmental flows (including ecological flows) (Petts 2009) was one of the first topics of ecohydraulics and has been a consistent emphasis at ISE symposia.. Initially, e-flows approaches (we use ‘e-flow’ for both to environmental and ecological flows) were purely “instream flow” approaches aimed at characterizing the flow regime that is suitable to integrate the life history requirements of a target species or guild of organisms (Tennant 1976). Gradually, purely “instream flows” determinations expanded to broader e-flows approaches that incorporate not only the life cycles and requirements of instream biota but biota in adjacent biotopes and ecosystems, such as riparian zones and floodplains, to finally include the water use requirements of a variety of stakeholders and end users (Arthington et al. 2018b, World Bank 2018). The spatial expansion of the science domain outside of the main channel was accompanied by an equivalent expansion in the participation of disciplines to include demographics, social sciences, environmental economics, tourism and recreational aspects through the valuation of ecosystem services (Logkariwar et al. 2014; Arthington et al. 2018a). E-flow science exemplifies the

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linkages between ecohydraulics and ecohydrology and demonstrates that these two disciplines can be complementary in holistic, long time and large-spatial scale applications.

Recent developments in remote sensing technologies and computing capabilities further integrate ecohydraulics and ecohydrology by allowing river scientists to collect high-resolution data over large areas (e.g. Orengo & Petrie 2017). "Remote sensing of rivers" is now even considered as a subdiscipline of river science (see Marcus & Fonstad 2010). For example, technologies such as LiDAR (e.g. Bowen & Waltemire 2007; Flener et al. 2013) and Terrestrial Laser Scanning (TLS; e.g. Heritage & Milan 2009; Williams et al. 2011) allow the large-scale collection of highly precise, accurate and finely resolved data. The use of Unmanned Aerial Vehicles (UAV) has become widespread, due to concurrent increasing computer power for post-processing of data and decreasing cost of purchase, for the mapping of river channel morphology and characterization of instream riverine features such as substrate or vegetation (e.g. Flynn & Chapra 2014; Viles 2016; Watanabe & Kawahara 2016; Hemmelder et al. 2018, Haas et al. 2019). Moreover, advances over the past decades in analytical, modelling (e.g. Harby et al. 2004; Fukuda et al. 2015; Kail et al. 2015; Brewer et al. 2018; Hernandez - Suarez & Nejadhashemi 2018; Melcher et al. 2018; Theodoropoulos et al. 2018) and statistical methods such as artificial neural networks (e.g. Muños-Mas et al 2018) and fuzzy logic (e.g. Mouton et al. 2009; Forio et al. 2017) allow processing and analysis of large quantities of complex data involving a variety of parameters to investigate the influence of multiple stressors on riverine systems. No doubt that the emergence of "Big Data" and Artificial Intelligence will also provide new tools to increase the spatial scale of

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application while conserving fine resolution. However, the question remains of the upscaling of ecohydraulics study results to entire catchments and few studies exist in that respect (Harby et al. 2017; Wheaton et al. 2017). One wonders if the same tools and disciplines can be used for the characterization and study of rivers as diverse as chalk streams or large floodplain.

Figure 3 highlights the relative positioning of ecohydrology, ecohydraulics, and river science while the array of disciplines that can be considered under the umbrella term of river science was presented in Table 1 and the potential for their integration and interactions is shown in Table 2. Three issues regarding the respective roles and focus of ecohydraulics and ecohydrology, and their integration arise:

Issue 1: Characterising the overlap zone between ecohydraulics and ecohydrology

Issue 2: The possible role of river science as a new unifying paradigm of which ecohydrology and ecohydraulics would be complementary components.

Issue 3: Generalising the ecohydraulics-ecohydrology continuum to other disciplines.

Achieving integration.

Issue 1: Characterising the Ecohydrology/Ecohydraulics Overlap Zone.

Ecohydrology and ecohydraulics focus on different characteristics and views of riverscapes (Wiens 2002) and use different tools and approaches to address them. Indeed, ecohydrological studies focus on the second characteristic/definition of a riverscape – rivers are linked to their surroundings by boundary flows and exchanges of energy and sediments- while ecohydraulics studies are more specifically focused

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on rivers as internally heterogeneous systems in their own rights. Focus realm and topic are thus another method for ordinating and interrelating disciplines and, thus, showing how they can be used to complement each other. The evolution of ecohydraulics partially results from the spatial connectivity among different aquatic systems, from freshwater to estuarine, coastal and marine and, the connectivity enables the expansion of this discipline towards new frontiers (Adams 2013; Rodriguez and Howe 2013)

It may be tempting, for the sake of complying with the principles of western science, which tend towards reductionism (Nestler et al. 2016a), to assign specific values of spatio-temporal scale to define the boundary conditions around the overlap zone between ecohydraulics and ecohydrology shown in Figure 3. However, it can be argued that to, arbitrary or not, assign a very specific number to define where a discipline/investigation of processes and phenomena ends and where the other begins does not fit with physical laws, and ecological processes and functions. On the contrary, the overlap between ecohydraulics and ecohydrology constitutes a fascinating frontier for new research. This should be taken advantage of and investigated using recent advances in technologies applied to river-related sciences, as previously described. Considering solely catchment scale processes in ecohydrology and instream processes at smaller spatial scales in ecohydraulics is counter-productive; it is important to integrate processes over both larger and smaller spatial and temporal scales both in ecohydrology and ecohydraulics. One possible way of achieving this is through organism-centered studies which integrate a variety of processes and disciplines to achieve a thorough understanding of organism ecology and life-history, the obvious example being fish (Nestler 2011). Through their life-

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history and habitat use, fish encompass all components of river ecosystems from very local sediment and habitat hydraulics to long migration routes and use of separate habitat for different life stages, e.g. adult mid channel habitat and floodplains nursery habitat.

Issue 2: A New Paradigm – the Role of River Science?

The use of "river science", or to define oneself as a "river scientist", conveys a more explicit message than that of being an ecohydraulician or ecohydrologist and enhances communication with lay audiences and members of other disciplines that study aquatic systems alike. The breadth of topics covered by river science and its inherent integrative nature are exemplified by the results of the search presented at the beginning in Figure 1, under the keyword "river science" in Web of Science. Furthermore, the question of the scale, which is one of the two central points of the ecohydraulics-ecohydrology integration, appears paramount in river science and can be used as a dimension to categorize disciplines within it, including disciplines other than ecohydraulics and ecohydrology, such as eco-geormorphology for example.

However, many scientists working in specific fields of interest would still probably like to define their work in more details or specific terms than the broad "river science". A hydrologist working with rainfall-runoff models to provide inflow information to support fish migration past a run-of-river hydropower plant, or an engineer designing a fishway past the same run-of-river hydropower plant, would probably not call themselves river scientists. The hydrologist may probably not even use the term "ecohydrology", but the engineer may be familiar with using the term "ecohydraulics".

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Issue 3: Generalize Ecohydraulics-Ecohydrology Continuum to other Interdisciplines?

We believe that other disciplines, both established and emerging, can be placed on a continuum similar to that of ecohydraulics-ecohydrology for the purpose of addressing specific issues in river science (Table 2). Among these disciplines are also relatively new interdisciplines that result from the phenomenon of "hyphenation" of hydrology and ecology (McCurley and Jawitz 2017). Foundation disciplines such as ecology, hydrology, geomorphology or biology are characterized by a strong set of establishing principles, from which subsequent interdisciplinary applications and research areas should benefit. As examples, we can cite hydromorphology, defined previously, and other disciplines, such as hydrochemistry, hydroinformatics, socio-hydrology (Wesselink et al. 2016), hydroclimatology, hydrogeomorphology or ecomorphology, among many others, imply interdisciplinarity in relation to hydrology (i.e. water) and they are based on disciplines with strong foundations, which makes their definition in terms of focus and scope easier.

One can wonder if this whole philosophical discussion matters or if it is, in the words of Shakespeare, "much ado about nothing". There is no simple, definitive answer because it depends on the aim of the scientists involved in this discussion. In the everyday use of scientific investigations, monitoring and data analysis, this sort of "identity questioning" does not occur to the majority of us. However, in an era of willingness and necessity to promote the discipline and our work to wider audiences, may they be stakeholders involved in an e-flow project, possible employers (particularly outside of academia), government agency, policy makers and funding agencies, it is absolutely paramount to establish a sense of identity. The identity must

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be achieved, not only by words (i.e. in the sense of communication and marketing) but also by the establishment of strong disciplinary foundations, principles and applications and a didactic approach as a backbone to allow further movement and progress, if we want to establish ourselves as a community and a recognized discipline. Ecohydraulics needs also to find its positioning with respect to other disciplines and current and emerging societal and scientific challenges, such as climate change.

4. Conclusion

First, ecohydrology and ecohydraulics should be considered complementary disciplines, not duplicative, even though hydraulics and hydrology are, in essence, very different disciplines. From an ecologist's perspective, trying to classify as being ecohydraulic or ecohydrologic can be counterproductive because the (co) development of the two disciplines was never coordinated. It is more important to consider how coupling concepts and new tools and technologies can advance river science to address issues of time and space scales, rather than worry about classification of a study as ecohydraulic or ecohydrologic. Nonetheless, awareness of these issues can facilitate addressing research gaps, integrating the various areas of research and would benefit communication and collaboration among scientists.

We support the argument for more consistency in the use of the terminology related to hydroecology, ecohydrology and ecohydraulics. It is evident and inevitable that some degree of overlap exists and will remain between these areas of research, as a result of their shared focus on water, flow, water resources and aquatic ecosystems, and the development of measuring and analysis techniques. This is revealed in the

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diversity of topics encompassed by each of the disciplines. Nonetheless, some topics remain discipline-specific. These should serve as basis to establish strong discipline principles and identity so that ecohydraulics can further find its positioning in science and society. The increasing trend of creating new integrative disciplines through juxtaposition of names to emphasize the specific focus of investigations, while providing a self-explanatory name to these narrower disciplines, may lead to an increasing scattering of scientific information and data and may restrict communication and collaboration amongst disciplines.

Advances in ecohydrology and ecohydraulics have driven new understanding of aquatic ecosystems because researchers are able to bridge gaps among disciplines by using coupling concepts (Figure 2). These link the different topics, technologies, and scales of ecologists, hydraulicians, and hydrologists, and, as a result, link instream processes to other compartments of the river system through an understanding of boundary dynamics among riverscapes.

Finally, terms like ecohydrology, ecohydraulics, freshwater biology or geomorphology (among others) are not necessarily well understood outside the scientific community. For communication outside academia and science, the term "river science" is a completely self-explanatory and understandable term that can immediately be recognized by society, encompassing more academic, mostly unknown, terms.

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TABLES

Table 1: Overview of the disciplines involved in the study of river systems that can serve as possible candidates for interdisciplinary integration.

Table 2: Topics and Issues Requiring Interdisciplinary Integration with Possible Team Compositions.

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Table 1

<table>
<tr><th colspan="5">RIVER SCIENCE</th></tr>
<tr><th colspan="2"><u>Natural/Environmental Science disciplines</u></th><th colspan="3"><u>Engineering (Applied) disciplines</u></th></tr>
<tr><td colspan="2">Biology</td><td rowspan="4">Civil Engineering</td><td colspan="2" rowspan="2">Environmental Engineering</td></tr>
<tr><td colspan="2">Ecology</td></tr>
<tr><td colspan="2" rowspan="2">Hydrology</td><td colspan="2">Water Resource Engineering= Hydrological Engineering</td></tr>
<tr><td colspan="2">Hydraulic Engineering</td></tr>
<tr><td colspan="2">Physics</td><td rowspan="5">Applied Physics</td><td>Environmental fluid mechanics</td><td rowspan="5">Hydroinformatics</td></tr>
<tr><td colspan="2">Freshwater Biology= Hydroecology</td><td rowspan="2">Hydraulics</td></tr>
<tr><td rowspan="2">Hydrobiology, Limnology = Aquatic Ecology</td><td>Ecohydrology</td></tr>
<tr><td>Ecohydraulics</td><td>Fluid dynamics</td></tr>
<tr><td>Climatology</td><td>Hydroclimatology</td><td>Hydrodynamics</td></tr>
<tr><td>Chemistry</td><td>Hydrochemistry</td><td colspan="3">Chemical engineering</td></tr>
<tr><td rowspan="3">Physical Geography</td><td>Geology</td><td colspan="3">Groundwater modelling</td></tr>
<tr><td>Hydromorphology/fluvial geomorphology</td><td colspan="3" rowspan="2"></td></tr>
<tr><td>Ecomorphology</td></tr>
</table>

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Table 2

General Applied Topics	Specific Applied Topics	Candidate Natural/Environmental Science Disciplines for Interdisciplinary Integration				Candidate Engineering (Applied) disciplines for Interdisciplinary Integration (and examples)			
		Biology / Ecology	Hydrology	Geology	Chemistry	Civil	Hydraulic	Chemical	Environmental Hydraulics
Environmental Flows	Hydrologic	X	X						
	Hydraulic	X					X		X
Physical River Restoration	In-channel Restoration & Habitat Feature Construction	X		X		X			
	Sediment Management	X	X	X			X	X	X
	Channel Realignment		X	X		X			X
	Dam Removal	X	X	X	X	X	X	X	X
	Flood protection	X	X	X		X	X		X
Fish Bypasses & Protection	Upstream	X	X			X	X		X
	Downstream	X	X			X	X		
	Fish-friendly Turbine Design	X				X	X		
	Physical/Behavioral Fish Protection System Design	X	X			X	X		X
Water Quality Management	Selective Withdrawal	X	X	X	X	X			X
	Aeration System Design for Reservoir Release Improvement	X			X	X		X	
	In Reservoir aeration/oxygenation systems	X			X	X		X	
Watershed improvement for sediment /contaminant run-off reduction		X	X	X	X			X	X
Riparian Zone Restoration		X	X			X			X
Hatchery Design		X				X	X		X

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FIGURES

Figure1: Distribution of scientific material with the keywords “Ecohydraulics”, Hydroecology”, “Ecohydrology” and “River Science” in ISI Web of Knowledge. The categories shown here are the 23 in which documents with the keyword “Ecohydraulics” were listed.

Figure 2:

Evolution of ecohydraulic (e.g., PHABSIM - Bovee et al, 1998 and ELAM - Goodwin et al. 2006) and ecohydrologic (e.g., IHA-Richter et al, 1996 and EFM - Dunn & Hickey, 2003) applications (A and B, respectively). Increasingly sophisticated coupling concepts keep pace with increasingly sophisticated hydraulic and hydrologic information to derive useful ecological information. Modified from Figure 2 of Nestler et al. 2016b.

Figure 3:

Venn diagram representation of hydraulics/ecohydraulics and hydrology/ecohydrology showing relative time and space scales over which each is applied (modified from Nestler et al, 2016a). Absolute time and space scales are dependent on the specific topic of investigation. For example, the time and space scales used to study an aquatic macroinvertebrate (mm or cm) vs. an adult sturgeon (m or dm) will differ substantially. Also, there may be considerable overlap where the application of either discipline pair may be appropriate. This is a very simplified view, for illustration purposes, of the place of ecohydrology and ecohydraulic and the breadth of river science. For a more complete overview of river science and its application, we refer to Table 1 and Table 2.

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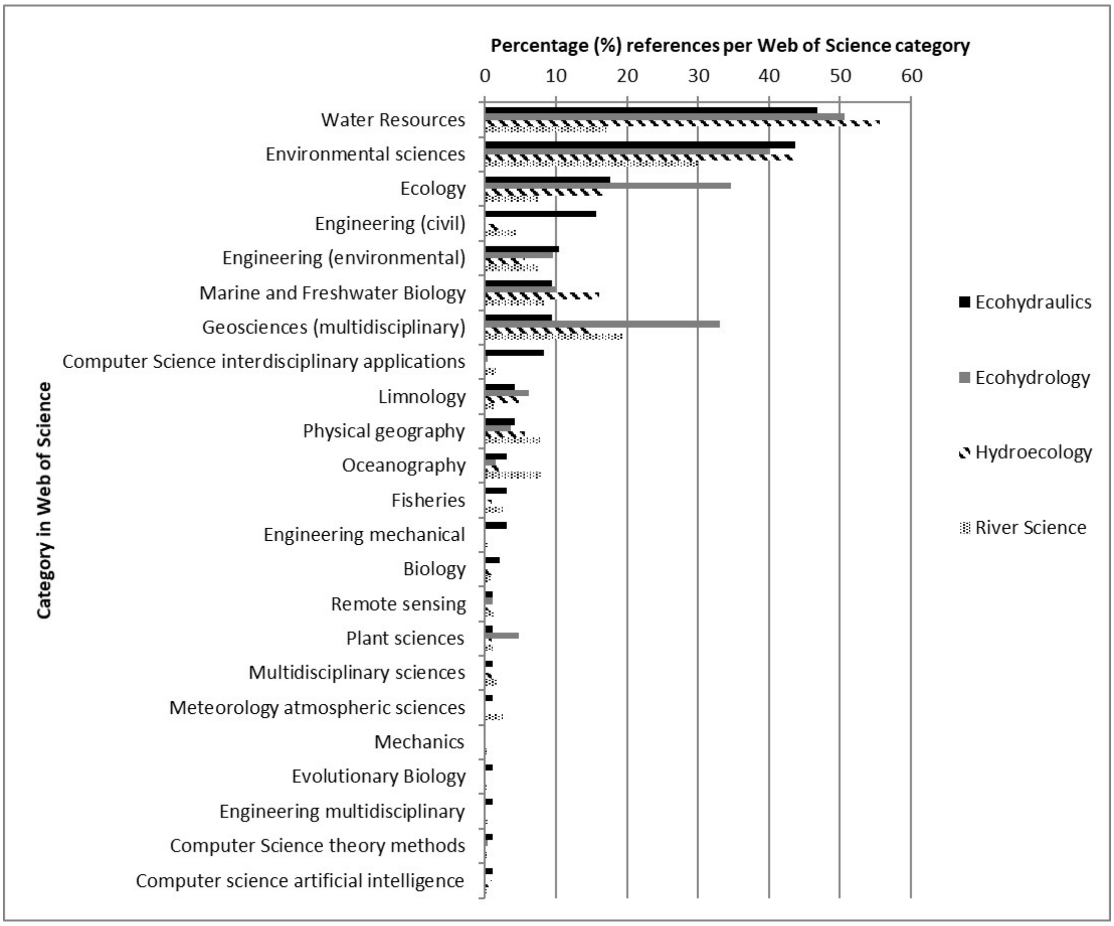

Figure 1

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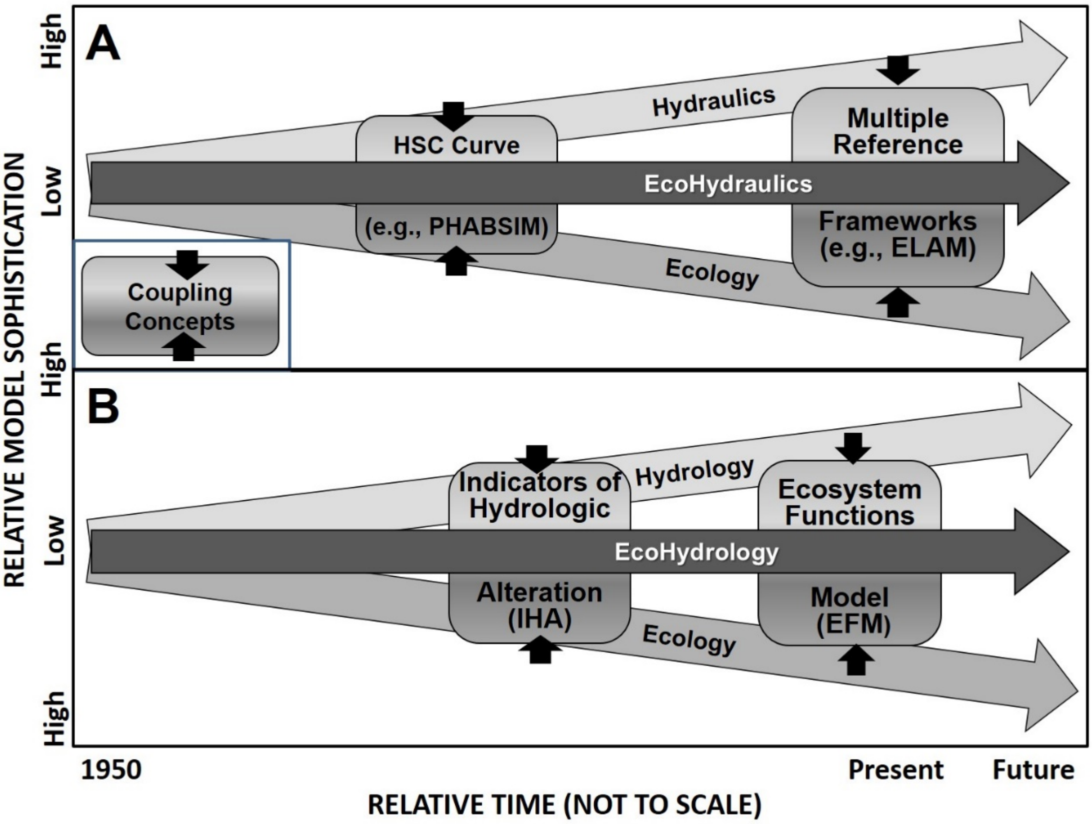

Figure 2

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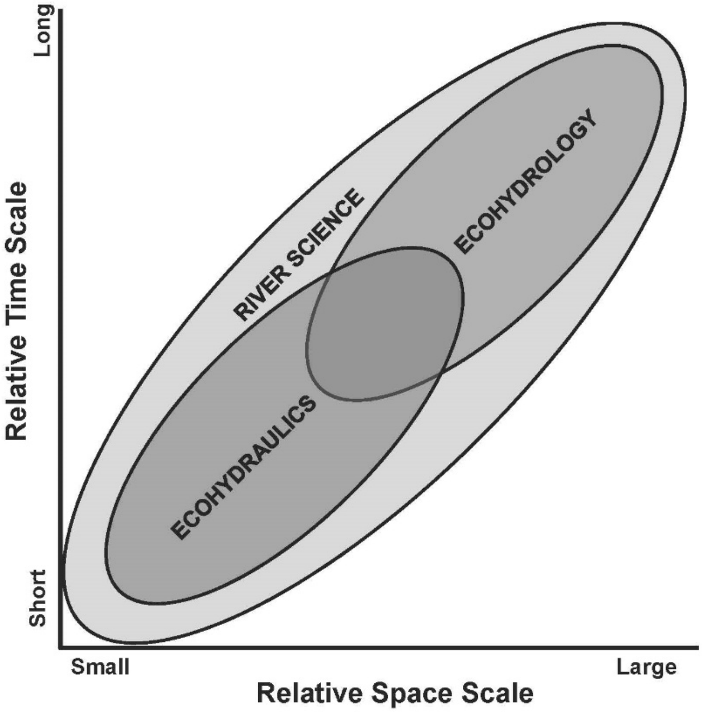

Figure 3

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