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ECOHYDRAULICS EXEMPLIFIES THE EMERGING "PARADIGM OF THE INTERDISCIPLINES"

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Abstract

The basic premise underlying ecohydraulics is deceptively simple: create a new discipline focused on the effects of water movement in aquatic ecosystems by melding principles of aquatic ecology (including aspects of fluvial geomorphology) and engineering hydraulics. However, advancing ecohydraulics as a synthetic, organized field of study is challenging because hydraulic engineers and ecologists: 1) study processes that differ substantially in spatial and/or temporal scale; 2) have very different approaches to modelling; 3) utilize different sets of mathematical formulations, concepts, and assumptions; and 4) address problems with vastly different patterns of complexity and uncertainty. The differences between engineering and ecology must be reconciled within a set of concepts and practices applicable to ecohydraulics. This reconciliation is essential if ecohydraulics is to achieve the scientific esteem of its parent disciplines. First, we review how the competing paradigms of determinism and empiricism structure engineering and ecology, respectively. We then derive two guiding principles that facilitate the integration of ecology and hydraulics, the Single Reference Framework and the Multiple Reference Framework Guiding Principles. Third, we provide illustrative examples of these principles using a simple hydraulic fish habitat analysis based on Physical Habitat Simulation (PHABSIM) system of the Instream Flow Incremental Methodology (IFIM) and a detailed fish movement model using Eulerian-Lagrangian-Agent methods (ELAMs). Based on these examples, we develop insights and conclusions to guide further advances in ecohydraulics and, perhaps even serve as a template to aid development of other inter-disciplinary fields.

Key words: Ecohydraulics; paradigm; Eulerian-Lagrangian-Agent methods (ELAMs); Instream flow incremental methodology, ecology; hydraulics

Introduction

Ecohydraulics: a search for understanding or practical applications?

Stokes (1997) categorizes scientific endeavors into a 2x2 matrix with rows addressing the question of “is the science a quest for fundamental understanding?” and columns addressing the question of “is the science a quest for practical use?” The resulting matrix has four quadrants with each quadrant containing a pair of values for “yes” or “no”. Particle physics is an example of a quest for fundamental understanding (“yes”), but without an immediate consideration of practical application (“no”). Pure applied physics (e.g., investigations conducted by Thomas Edison) is an example of research to solve practical problems (“yes”), but without a quest for fundamental understanding (“no”). Louis Pasteur’s research into vaccination, microbial fermentation, and pasteurization melded the two quests (“yes”/“yes”) to perform ground breaking research focused on saving human lives.

In many respects, ecohydraulics presently falls into Thomas Edison’s quadrant in that applied research is conducted to address practical problems such as environmental flows, fish passage designs and operational criteria, and river restoration technologies. We wonder if, in its quest to address practical problems, ecohydraulics as a community of practice has dedicated sufficient energy into fundamental understanding. We believe that the future growth of ecohydraulics as a discipline must include an element of fundamental understanding to help ecohydraulicians grow ideas and concepts in a synthetic and organized manner. Using Stoke’s matrix as a metaphor, ecohydraulicians must migrate from their present position in Edison’s quadrant to relocate in Pasteur’s quadrant if they wish to achieve the scientific stature of the parent disciplines of ecology and hydraulic engineering.

We believe the primary barrier preventing the migration of ecohydraulics from Edison’s quadrant into Pasteur’s quadrant is a lack of fundamental concepts and practices, a problem shared by many new interdisciplines (e.g., Socio-hydrology) and interdisciplinary academic programs. The commonality and magnitude of this problem implies that its solution should be sought at a paradigmatic level. A paradigm is best defined by example. Isaac Newton’s foundational book “*Philosophiae Naturalis Principia Mathematica*” (often simplified as “*Principia*”) created a framework of concepts, results, and procedures (i.e., a paradigm) that structured subsequent work for hundreds of years (Kuhn 1962). “Normal” (i.e., non-quantum) science proceeds creatively and flexibly within such a framework. The first step in the creation of an interdiscipline with a paradigmatic foundation is the development of guiding principles. A guiding principle (sometimes termed an organizing or a fundamental principle) is a general scientific theorem or law having many special applications across a wide field. For example, conservation laws for mass, momentum, and energy (Cebeci and Bradshaw 1988) represent a powerful set of guiding principles that are still the foundation for many physicochemical-based disciplines hundreds of years after they were originally proposed. Without guiding principles, scientific advances occurring in disciplines in Edison’s Quadrant run the risk of developing spasmodically as isolated and disparate events not integrated within a greater framework. The resulting technology fragmentation hinders efficient creation of new tools and technologies; results in confusion, poor communication, and duplication of effort; and impairs preparation of the next generation of practitioners. Our goal is to encourage a synoptic perspective of ecohydraulics by proposing guiding principles for ecohydraulicians. We focus specifically in this paper on flow-fish interactions because it is a dominant theme of ecohydraulics (e.g. at the recent 11th International Symposium on Ecohydraulics, 23% of coherent ‘topics’ within the proceedings examine flow-fish interactions (Webb et al. in prep). Further work is needed to develop or add to fish-flow interactions to confirm guiding principles that apply to other areas of Ecohydraulics and have broad acceptance across the Ecohydraulics community.

Solving the Apples and Oranges Conundrum for Interdisciplines

Reductionism causes fundamental terms in different disciplines to have subtle differences in definition that complicate interdisciplinary communication and integration. These differences must be reconciled for full integration to occur. The physics-based paradigm of determinism includes specific approaches for observing and describing physical phenomena, and formulating physical laws. The approaches usually consists of an observer, coordinate system, and clock (collectively termed a reference frame) that allow scientists to describe and explore the natural world. The observer is usually defined as a single, abstract person observing a process of interest. The choice of a reference frame for analyzing the spatio-temporal variations of aquatic ecosystems is particularly important for ecohydraulics because there is a potential for mismatch in process-scales between hydraulics and ecology (Nestler et al. 2016). It is certainly worth considering the applicability of classical Eulerian (i. e., a fixed probe characterizes passing constituents) and Lagrangian (a mobile probe moves with a specific particle) points of view, widely used in hydraulics, to ecohydraulic systems. To facilitate the conceptual integration of hydraulics and ecology, it is useful to expand the usual physics-based definition of frame of reference to include biological and ecological concepts to more fully integrate hydraulics and ecology. In this expansion, we consider the observer to represent the perspective of a discipline or sub-discipline. For example, a meta-population modeler may adopt a coarse representation of time (annual or monthly increments) and space (river reach scale) (Hanski and Gilpin 1991) compared to a biomechanist's fine representation of time (fractions of a second) and space (mms or cms) (Liao 2007). To avoid confusion, we term this expansion of the reference framework as a structure of concepts, ideas, and conventions by which a group perceives or evaluates data or simulates natural systems. Using the expanded definition of reference framework, many other systematic approaches to aquatic science could also be included within ecohydraulics such as specific elements of cognition, bioenergetics and population modeling that are compatible with the classical definition of reference frame. Importantly, the universe around us is neither exclusively nor completely defined by any single reference framework. Rather, each reference framework is a useful simplification of reality allowing individual scientists to understand and communicate the workings of a subset of the total universe associated with their particular discipline. For epistemological reasons, it is useful to contrast the terms "paradigm" and "reference framework" because they appear similar. For purposes of this paper, we use "paradigm" to imply broad philosophical or conceptual topics (e.g., discussions of scale or causality) whereas "reference framework" implies implementation topics (e.g., choice of a reference frame or other broad methodological topics).

The history of science teaches that a discipline radiates from its inception on a template of its guiding principles. It becomes increasingly specialized by simplifying complex phenomena into simpler or more fundamental levels (i.e., scientific reductionism) until a sufficient explanation is achieved. We believe practitioners of a discipline can achieve a synoptic perspective when they understand the history of its guiding principles and how these principles relate to the discipline's scientific advances. In addition, ideas and concepts have intellectual momentum so that their ever-evolving form and pattern provide insight into the advances of future. Practitioners who understand the guiding principles of their discipline are able to help forge future directions and optimally invest in equipment, train staff, and generally prepare for future opportunities. Most importantly, students can make informed career decisions because they are able to identify particular growth areas or topics of their selected discipline. By clarifying the evolving principles of a discipline, there is also the opportunity to expose weaknesses, providing fertile ground for new ideas and research directions to emerge where they are needed.

Developing guiding principles

Present State of Guiding Principles

Ecology and hydraulics, the constituent disciplines of ecohydraulics, each already have unique guiding principles. For example, entry-level students in Engineering or Ecology will take foundational courses using text books such as “Fundamentals of Hydraulic Engineering Systems” (Houghtalen et al. 2010) or “Fundamentals of Ecology” (Odum and Barret 2004), respectively. We were unable to find a text book on the principles or fundamentals of ecohydraulics, although we recognize the recent book “Ecohydraulics: an Integrated Approach” by Maddock et al. (2013) as a compendium of important papers. The papers presented within Maddock et al. (2013) are organized into three parts: “Methods and Approaches”, “Species-Habitat Interactions”, and “Management Applications Case Studies”. As a body, these papers best fit in Edison’s quadrant. We were unable to find any papers that would fit into either Newton’s or Pasteur’s quadrants, although the introduction provides useful history and context for ecohydraulics as a discipline.

Separating complex human activities such as science into strata using a hierarchical perspective provides useful simplifications to aid understanding. Figure 1 represents a hierarchy that describes the organization of traditional or “normal” (i.e., non-quantum) science tailored to ecohydraulics. In this representation, the more foundational (lower) levels serve as an organizational template for the less foundational levels (higher). Typically, researchers working within each of the strata exhibit different (but complementary) motivations, depending upon their personality, interests, background, and training. The professional productivity within each layer depends upon the availability of specific enablers. For example, the performance of ecohydraulics applications requires tools, funding, and facilities. To understand ecohydraulics it is necessary to understand the motivations and enablers for each stratum. In our assessment of ecohydraulics, the two most foundational levels of ecohydraulics (the Discipline and Paradigm strata) are poorly developed. For example, if we classify papers in “Ecohydraulics: An Integrated Approach” by stratum then we see that the bulk of the papers are application or methodology based. We believe that the underlying reason for this distribution of papers is the lack of enablers – specifically, the lack of guiding principles within ecohydraulics. We believe that ecohydraulics has existed sufficiently long, with an extensive set of literature, that we should now be able to concentrate on constructing guiding principles to help structure and organize our discipline. Our goal is to make the case for increasing focus on these fundamental aspects and contribute to the development of the two bottom strata by proposing guiding principles for ecohydraulics.

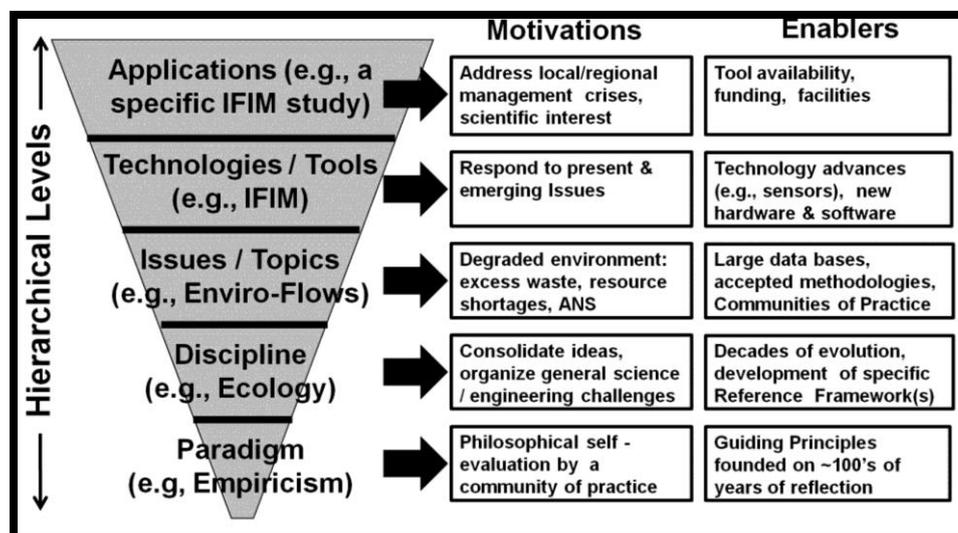


Figure 1. Hierarchical organization of science and its relationship to ecohydraulics.

Different scientific disciplines diverge over time as the tools and understanding of each become increasingly refined. This divergence results in classical scientific reductionism wherein a complex phenomenon is progressively reduced into simpler, but more specialized, phenomena representing more fundamental levels until no further reduction is possible, at which point first principles are reached *sensu* Aristotle (350BC). Along the journey to first principles, each discipline will pursue its own research agendas and, in the process, develop separate (and occasionally mutually exclusive): concepts for metering time and space; methods for dealing with uncertainty and causality; lexicons and terminologies; and means of quantifying scale and scale effects. Eventually, members of each discipline (or those who study disciplines) consolidate and analyze the progress and status of a discipline to develop its guiding principles. We can make three useful statements about guiding principles for ecohydraulics based on deductions from general statements about the ontology of science:

- [1]Ecohydraulicians cannot construct new guiding principles for either ecology or hydraulics. Both disciplines are relatively mature and have evolved their own, often unique, guiding principles. However, as we have experienced, it is possible and often necessary to modify discipline-specific tools to increase their value for interdisciplinary application.
- [2]All guiding principles of ecohydraulics will be integrating or linking concepts that allow ecohydraulicians to reverse scientific reductionism and achieve a measure of holism. Integrating principles are critical to the development of a new holism that allows scientific insights to be gained by ecohydraulicians that are beyond the reach of either ecologists or hydraulicians.
- [3]The procedures we use to develop guiding principles for ecohydraulics may have extension to other interdisciplines in which the parent disciplines are very different. That is, we may contribute to the development of a science philosophy broadly applicable to interdisciplines.

The Single Reference Framework Guiding Principle

We develop two guiding principles of ecohydraulics based on a simplified history of the relationships among ecology, hydraulics, and ecohydraulics (Figure 2) during four time periods. Prior to 1975 there were relatively few studies to integrate stream hydraulics and ecological response, although some state resource department personnel in the USA were conducting studies to describe hydraulic criteria for either salmon spawning or passage of adult salmon across shallow sections of a river. However, all of these early studies were based on field measurement of hydraulic condition or the use of stage discharge data from nearby gauges (Bovee 1975). In later studies, habitat would be described in cells along a transect (e.g. Bovee 1981). In 1976, the US Department of Agriculture Soil Conservation Society (1976) released WSP2 (for Water Surface Profile), one of the first computer-based hydraulic programs that could be used to simulate river stages at cross sections. Early workers realized that a modified version of WSP2 that could simulate depth and velocity conditions within cells at specific discharges could be integrated with the concept of habitat suitability criteria to produce the first widely used, recognizable ecohydraulics tool – the Physical Habitat Simulation (PHABSIM) System of the Instream Flow Incremental Methodology (IFIM). The PHABSIM was widely used to address environmental flow issues, particularly from the time period of 1975-1995. A number of physical analysis systems have been developed that are conceptually similar to the PHABSIM System (see review in Tharme 2003).

A critical assumption underlying the PHABSIM and similar methods is the consistency of scale between the methods used in quantifying cell discharges with the methods used to define instream physical habitat. If the scale used to estimate discharge is similar to the scale used to estimate habitat, and a strong association between physical conditions and fish occurrence can be established, then it is possible to use a conversion function (analogous to a currency exchange rate) to exchange values of depth and velocity in a cell to habitat quality in the same cell as

$$\text{Habitat value} = f(\text{depth and velocity})$$

(1)

The PHABSIM uses solely an Eulerian representation of the stream channel; depth and velocity are represented by mean values or associated with mean values (e.g., nose velocity can be calculated from a velocity distribution associated with mean velocity), and the representation of the stream environment usually involves either a single scale or a limited range of scales. The PHABSIM and other related methods are a major feature of Ecohydraulics. All of them assume that influences of flow on fish populations are represented by the local habitat conditions and the spatial arrangement of hydraulic conditions is considered to be largely irrelevant. Some utilize a frequency distribution of hydraulic conditions as a sufficient description of the hydraulic environment for analysis, and this approach to fish habitat modelling has been successful (Lamouroux et al., 2015).

In addition to consideration of average depth and velocity, a typical application of the PHABSIM also involves consideration of a variable representing fish cover. Cover is usually defined in geomorphic terms (e.g., sand or cobble), although other definitions are possible (e.g., low hanging branches could be defined as “overhead cover”). For purposes of this paper, we will restrict our discussion to considering cover as a geomorphic variable. Within PHABSIM and related methods, cover is treated as a constant although the importance of quantifying channel change as a function of hydraulic conditions is known to be important in habitat assessment (Lorang and Hauer 2003). Therefore, the general formulation of the habitat suitability index models used in the PHABSIM system inherently integrates biotic habitat selection, simple hydraulic model variables, and a simple geomorphic index. This suggests that at least parts of the fish habitat-fluvial geomorphology relationship can be considered within the same conceptual framework as fish-flow relationship.

The conceptual consistency between certain elements of fluvial geomorphology and aquatic habitat methods even precedes the development of the PHABSIM. Prior to the development of the PHABSIM and related approaches, early practitioners of environmental flows depended upon hydrologic methods to relate instream habitat to reach scale hydrologic pattern. For example, the Tennant Method (Tennant 1976) relates percentages of the average annual flow to the following ecological responses: minimum of 10% sustains short term survival, 30% sustains good survival and recreation, and 60% supports excellent aquatic habitat and recreation. These relationships are very similar in form to studies that relate reach-scale discharge and sediment supply to erosion of and deposition of noncohesive sediments in alluvial rivers (Lane et al. 1995). In a very simple case, an alluvial channel comprised of unconsolidated sands may erode under high velocity gradient conditions and low sediment supply, or aggrade under low velocity gradient and high sediment supply conditions. Once the erosion threshold is exceeded, then sediment transport is determined by the water velocity field. In this simple case, it is possible to convert hydraulic variables (i.e., either velocity or velocity gradient) into an estimate of a geomorphic process such as bed load transport or channel evolution. In both cases, relatively coarse hydrological information is related to relatively coarse response variables. At a finer resolution, there is a long history of using classification to identify specific morphological units (e.g., riffles, runs, pools) in attempts to align them with fish habitat units (Nestler et al. 2016). In both fluvial geomorphology (Land and Richards, 1997) and fish habitat analysis there has been an increasing appreciation of the importance of considering a range of scales (including the previously-ignored fine scales) to better understand the ecology of rivers with a change in emphasis from description to understanding and explanation (Nestler et al. 2012).

Similarity in the methods used to describe or simulate changes in fluvial geomorphic patterns as a function of discharge, with the methods used to simulate changes in aquatic habitat patterns as a function of discharge (e.g. Maturana et al. 2014), implies the existence of underlying guiding principles. We propose the Single Reference Framework Guiding Principle as a guiding principle of Ecohydraulics, through its formative years as exemplified by the general methods used to describe reach scale aquatic habitat or sediment dynamics and the development of PHABSIM and allied approaches. All of these cases employ an Eulerian frame of reference (either explicitly or implicitly), and the scales used to approximate hydrological or hydraulic conditions are approximately equal to the

scale used to study the response of either aquatic habitat or geomorphology. In some cases, the scales may be at the reach level (e.g., the Tennant Method or methods described in Lane and Richards, 1997), and in other cases the scales may be at an intermediate meso-habitat scale (Parasiewicz 2007). If the scale-compatibility requirement is met then a conversion function can be developed and tested to exchange values of hydraulic variables into unique values of ecological or geomorphic responses. The robustness of the conversion function will be dictated by the strength of the statistical or mechanistic relationship among the hydraulic variables and the response variables. Once fully developed, a habitat conversion function can be applied at the transect cell level to accumulate habitat values into reach summaries to support scenario analysis. Alternately, a geomorphic conversion function can be applied at the reach or transect scale to estimate bed load transport or the onset of erosion or deposition. The Single Reference Framework Guiding Principle (where the inherent scale of ecological and hydraulic variables is approximately similar within one study) has been successfully used to address environmental flow issues for decades and continues to be employed where the necessary assumptions are met.

We note that the PHABSIM, although widely used throughout the world, has been criticized for its lack of biological realism, inability to demonstrate a positive relationship between fish habitat and fish abundance, and other reasons (Gore and Nestler 1988; Mathur et al. 1985; Shirvell 1989). The use of PHABSIM or conceptually similar methods inadvertently creates a focus on restoration of physical habitat while ignoring the many other possible causes of population decline because they are outside the scope of the methodology (the myth of the field of dreams – build it and they will come) (Hildebrand et al. 2005). However, it becomes clear that the limitations of any of the simpler methods (analytical solutions and index concepts) and methods based on the Single Reference Framework Guiding Principle (left hand two blocks in Figure 2) are inherently less realistic because of the simplifying assumptions required to use the Eulerian reference frame, their inability to reconcile multi-scale processes, and their limited ability to simulate complex processes. These limitations create unrealistic and unwarranted expectations of restoration success that have fueled the frustrations of students of both ecology and geomorphology. However, these limitations are not necessarily a fault of the methodology, but rather are a manifestation of the inadequacy of the Single Reference Framework Principle when viewed from a broader philosophical perspective.

The Multiple Reference Frameworks Guiding Principle.

In many cases the simplifying assumptions of the Single Reference Framework Guiding Principle may be too restrictive to address certain important ecohydraulics applications. The assumptions of the Single Reference Framework Guiding Principle are violated if:

- Target aquatic organisms may be responding to a flow regime across multiple locations instead of the hydraulic conditions within their specific cell. For example, a migrating fish in a high-energy section of the river (i.e., high slope and high velocity), may select a migration corridor of relatively high velocity because there is no low-velocity corridor. In contrast, in a low energy section of the river, a migrating fish may select a migration corridor of substantially less water velocity. A single swim path selection criterion-based approach will not be able to accurately forecast in both settings.
- The habitat characteristics of a target organism may be influenced by non-hydraulic internal or external conditions. For example, a fish's choice of habitat may be motivated by a variety of internal (e.g., degree of hunger, reproductive status, migration status, or parasite load) or external (e.g., socially antagonistic interactions, poor water quality, or presence of predators) conditions.
- Memory of past conditions, acclimation, or other cognitive processes are an important element of habitat selection.
- Physiological, bioenergetics, or biomechanical investigations are being conducted in a way that aquatic organisms need to be considered individually. Individual particle identity is lost in a classical Eulerian reference frame.

In the cases described above, the Single Reference Framework Guiding Principle is inadequate and a Multiple Reference Framework Guiding Principle must be used. The key to understanding the Multiple Reference Framework Guiding Principle is the observation made above that the universe around us cannot be completely defined by any single reference framework. Rather, each reference framework is a useful simplification of reality that allows scientists to understand and communicate the workings of a system within their particular discipline. Therefore, the foundation of interdisciplinary integration is to understand and then conceptually and mathematically integrate the reference frameworks of each discipline using the Integrated Reference Frameworks Concept (IFRC) (Nestler et al. 2008). This concept was developed as an idea to address multi-scale environmental problems (e.g., Nestler et al. 2008). The ideas within the IRFC are implemented with Eulerian Lagrangian Agent Methods (ELAMs – Goodwin et al. 2006). ELAMs have been used successfully to address downstream passage by out-migration juvenile salmon on the Snake and Columbia Rivers of the USA (Goodwin 2014). Note that the components of the problem are distributed into three reference frameworks and each reference framework is suited to its component of the problem. Therefore, use of the Multiple Reference Frameworks Guiding Principle will always be more accurate and realistic than use of a Single Reference Frameworks Guiding Principle for complex, multi-scale problems.

The development of ELAMs is linked to advances in computational fluid dynamics (CFD) modeling. CFD models create highly resolved, accurate descriptions of complex flow and water quality fields in rivers, estuaries, and reservoirs that far exceed the capabilities of the early hydraulic models that led to the development of the IFIM and other ecohydraulics tools prior to ~1995. In an ELAM, physical and chemical patterns are represented in the Eulerian reference framework (i.e., fluxes of water or chemical constituents move through a stationary grid or mesh). Living resources are represented by the Lagrangian and agent reference frameworks. The traditional Lagrangian reference framework is used to create particles that maintain their separate identities as they are transported within a grid or mesh (unlike in the Eulerian framework where individual identity is lost). In the agent portion of ELAMs, a cognition algorithm is used to create a “smart particle” that acquires information about its surroundings, processes the information, and then executes a movement behavior (or other behavior) based on one of several different motivations (e.g., to feed, swim with a school, or to migrate upstream). The ELAM is not bound by some of the limiting assumptions of Single Reference Framework Guiding Principle. However, it may be substantially more difficult to implement because the user must be familiar with CFD modeling, particle tracking, principles of sensory systems and cognition, and animal behavior.

We propose the Multiple Reference Framework Guiding Principle as the second principle of ecohydraulics. The core of this principle is the use of mathematical translators that can convert and rescale information in the Eulerian reference framework so that it meets the requirements of the Lagrangian and Agent reference frameworks. For example, information from a mesh node (or face or center depending upon the mesh typology) is usually interpolated to a location representing either a passive particle or a virtual fish since their position seldom falls exactly on a mesh node. Additional information can be interpolated to populate the sensory envelope of a virtual fish so that the type and scale of information available to a real fish is also available to the virtual fish making the resulting simulation is as realistic as possible. Creation of a cognitive algorithm that attempts to duplicate decision-making by a target aquatic organism allows ELAMs to create virtual realities within which virtual biological entities can move in realistic ways. The use of the additional reference frameworks allows ELAMs to make fewer assumptions, and thus reduce output uncertainty, than single-reference framework approaches (Goodwin et al. 2006).

The ELAM example integrates the Eulerian, Lagrangian, and agent frameworks (cognition), but the concept can be extended to other potential topics for ecohydraulic analysis (Figure 2). For example, the ELAM can be expanded to create and analyze virtual fish combining cognition with

realistic bioenergetics responses so that swimming speed – fatigue effects of fish passage (Figure 3) can be evaluated (Smith et al. 2014). Although not routinely performed as part of applied ecohydraulics, biomechanics and bioenergetics studies can be made routine by evaluating the forces acting on fish as they swim through complex flow fields (Laio 2007). Studies of incipient motion of channel gravel (Papanicolaou et al. 2002) and stream bed stability (Lorang and Hauer 2003) could be used to extend the boundaries of ecohydraulics into geomorphology research., but would require creation of an enabling mathematical infrastructure similar to that used to implement ELAMs but focused on fluvial geomorphological processes.

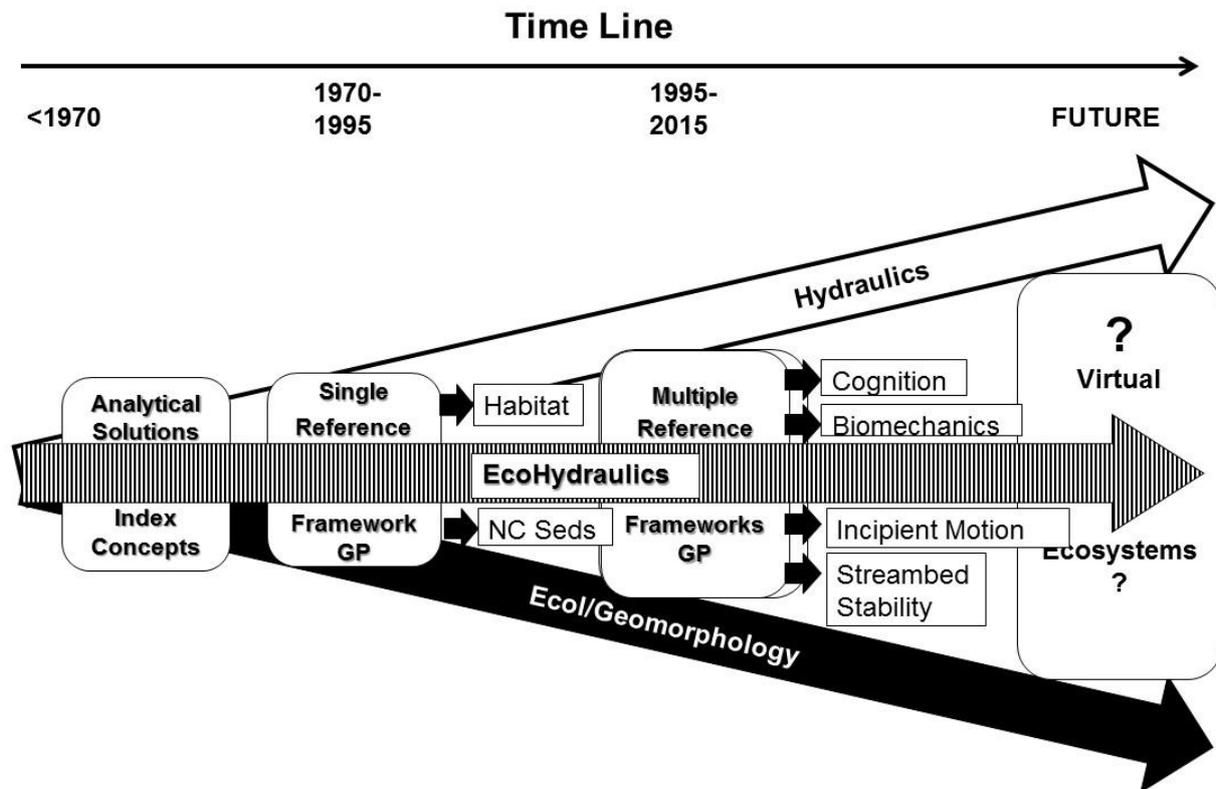


Figure 2. Schematic representing scientific reductionism in the development of ecology and hydraulics and the increasing difficulty of integrating the two trajectories into ecohydraulics. Early in the history of Ecohydraulics approaches, the lack of computational resources relegated tools to either analytical or index solutions, With further development and the availability of early computers, Ecohydraulics transitioned to the Single Reference Framework Guiding Principle (GP) using primarily the Eulerian reference frame. In this phase, practitioners were able to address relatively simple habitat analyses and dynamics of non-cohesive (NC) sediments in alluvial rivers. In its present state, Ecohydraulics can employ the Multiple Reference Frameworks Guiding Principle to integrate across disciplines. The Multiple Reference Frameworks Guiding Principle allows integration of many additional subdisciplines to Ecohydraulics including cognition (ELAM), bioenergetics, biomechanics, and other topics that require highly resolved information. This figure implies accumulation of tools and not replacement over time because the simpler tools are still relevant and useful as long as the assumptions behind their use are not violated.

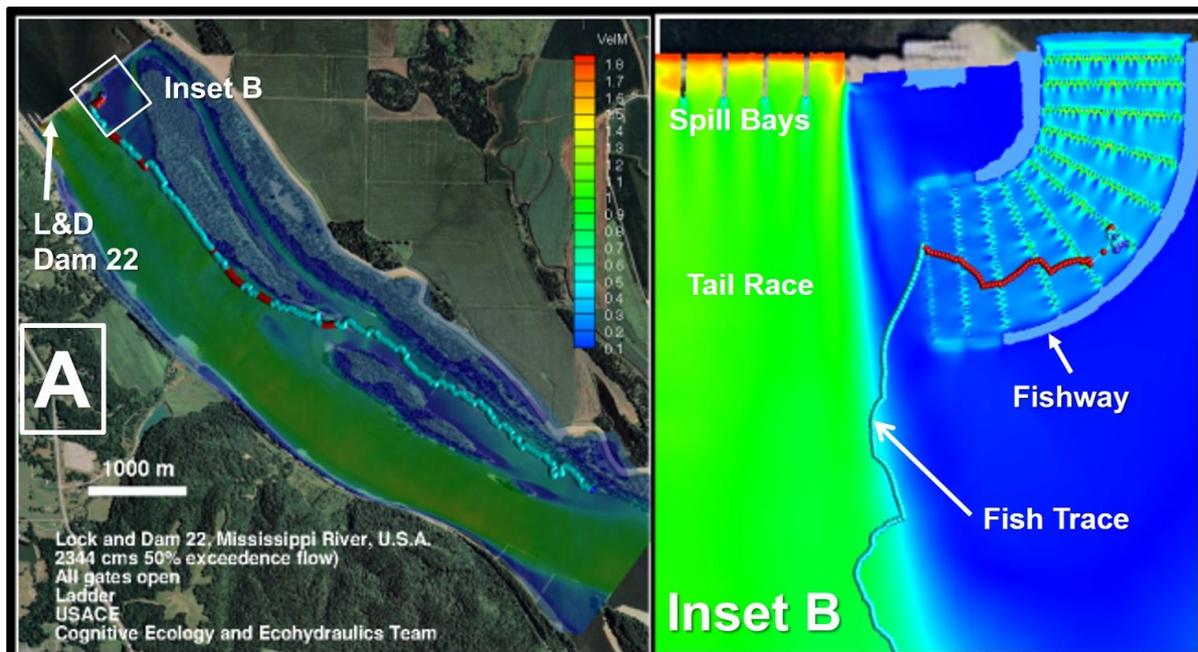


Figure 3. Example output from a typical ELAM model showing velocity contours (representing Eulerian reference frame), trace made by virtual fish (representing Lagrangian and agent reference frames).

Discussion and Summary

Holism and Reductionism

Ecohydraulics represents an integration of two very different paradigms that historically have been mutually exclusive or nearly so. Therefore, the successful integration of these two paradigms provides a template for other interdisciplines (integrated disciplines) such as socio-hydrology that also merge different disciplines. We hope that the development of linking principles such as those described in this paper will inspire others who are working in interdisciplinary areas. Finally, interdisciplines like ecohydraulics have the ability to reverse the normal tendency towards scientific reductionism by enabling a more holistic perspective by their practitioners. As scientists grapple with increasingly complex, ecosystem-level problems, their ability to interact on shared reference frameworks will result in more realistic depictions of the natural world and more efficient identification of problem solutions and new technologies. For example, the ELAM approach led to a description of how fish movement behavior and habitat selection, fluid dynamics, fluvial geomorphology, and biogeochemical cycling are interrelated (Nestler et al. 2012). This understanding would not have been possible using a single reference framework approach. We believe that use of the two guiding principles identified in this paper will offer a way for scientists to achieve a holistic perspective and develop the next generation of integrative tools. At a minimum, we hope to stimulate an active discussion on the best methods to reverse scientific reductionism.

Moore's Law, and the Future of Ecohydraulics

“Where are the undiscovered scientific territories?” is one of the critical questions plaguing all disciplines. How should practitioners invest their time, direct their students, and update their core competencies to anticipate new technologies that might arise in the future? Our historical analysis of ecohydraulics uncovered a rise in model complexity dictated by Moore's law (i.e., the density of transistors in an integrated circuit doubles approximately every two years). CFD models that use fine-scale resolution and short time steps to simulate large geospatial domains are computationally demanding and were generally unavailable before about 1995. Prior to this time period, the only

viable technologies for ecohydraulics use were based on the single reference framework principle. Ecohydraulicians could not develop multi-scale principles such as particle tracking methods or ELAMs until the advent of advanced CFD models made possible by advances in computer technology. This pattern is likely to persist into the future. Ecohydraulicians should be able to develop and explore new ways of coupling ecological processes to CFD models. We speculate that future ecohydraulics applications may be based on discrete element simulations of swimming fish, a method presently restricted to the research realm (e.g., Borazjani and Sotiropoulos 2008). In the near future, it may be possible to include additional environmental variables that can be described using the Eulerian reference framework such as bubble curtains or electric fields to assess fish barrier designs.

A major challenge for future research is to relate longer-term (i.e. multi-year) fish population dynamics to movement behavior of individual fish at local time and spatial scales in response to the hydrodynamic environment. There is a growing number of studies modelling fish population dynamics (e.g. Gotelli and Taylor 1999) but it is rare for flow effect to be explicitly represented (e.g. Perry and Bond 2009). However, if local flow conditions have important effects on individual fish movement, energy expenditure or access to resources, then it seems reasonable to expect that fish population dynamics are similarly affected as an aggregate response of these individual effects. There is an opportunity to develop principles and approaches for studying these aggregate flow effects on fish population dynamics and specifically rates of recruitment, mortality, emigration and immigration. However there are major challenges related to complex bio-physical interactions to address this challenge (Rose 2000).

Simplicity vs. Complexity in Ecohydraulics

The parsimony principle attributed to William of Occam (Occam's razor) dictates that simpler explanations (by extension simpler models) should be more useful and effective than complicated explanations (complicated models). The latter category of models run the risk of being so over-parameterized that accurate simulation of causal relationships is replaced by the tuning of multiple model parameters until model output matches a calibration data set. Use of such models in ecology has been derisively termed "Fortran ecology" (Odenbaugh 2003). The continued evolution of remote sensing technologies to generate increasingly more resolved maps of the physical domain of aquatic systems coupled to the increasing spatial and temporal resolution of CFD models leads to a quandary for ecohydraulicians – "How much model complexity is needed in an ecohydraulics application?"

The answer to this question first must recognize that the causality structures of hydraulics and ecology are different (Nestler et al. 2016). A deterministic discipline like hydraulics assumes a high knowledge of the causal structure in the natural world to the point that an equation (the governing equation) appears to control fluid motion. As a consequence of this 'high causal resolution', the derivation and proper application of different hydraulic models are well established. For example, "Mannings Equation" commonly used in open channel flow analyses was introduced in 1889 and the Navier-Stokes equations of fluid motion upon which many CFD models are based were derived independently by Claude-Louis Navier in 1822 and George Gabriel Stokes in the 1840's. In contrast, responses of populations or communities of aquatic organisms to their environment can be influenced by wide array (and usually mostly unknown) of internal states, external stimuli, external conditions, behavioural interactions, effects of predators and competitors, and many other factors (Levins 1966).

Therefore, in an ecohydraulics application, the choice of model complexity will be determined primarily by knowledge of the causality structure of the ecological component. For example, an investigation of a population response to flow alterations may use a relatively simple representation of physical habitat such as a hydrologic or meso-habitat approach. In this application, the population model will be relatively simple and by necessity ignore the influences of many factors that are difficult or impossible to measure. The supporting hydraulic model can be equally simple because the low causal resolution of the population model makes finely resolved hydraulic output irrelevant. In

contrast, an investigation of the swimming bioenergetics of a single fish in a swimming chamber would be best supported by a finely resolved, dynamic CFD model. In this application, causal resolution is high because the fish must respond to the hydraulic environment of the chamber if other factors such as condition of the fish or the water quality of the chamber are controlled. The optimum model complexity for different ecohydraulic applications will become clearer with experience. Part of this consideration is what Ward (2008) describes as the ‘simplicity cycle’. In the cycle, in first tackling a problem, a naively simple solution must be used because of a lack of knowledge, but this solution does not perform as well as desired. As knowledge builds over time, the solution is refined with increasing levels of causal resolution to the point where it performs well, but is complex and potentially difficult to use. With further time, however, understanding improves and opportunities to remove complexity without compromising performance emerge. The endpoint of the simplicity cycle is an elegant solution of ‘requisite simplicity’ (Rogers 2007) that could only emerge by taking the full journey through naïve simplicity and informed complexity.

We believe these concepts apply equally to the development of ecohydraulics, and indeed much of this chapter can be viewed through the lens of the simplicity cycle. Early approaches, constrained by a lack of computing power, relied on analytical solutions and indices (Figure 2). These were useful, but did not sufficiently well capture the dynamics of even relatively simple ecohydraulic problems. The single reference framework improved this, but also led to an appreciation that processes operating at multiple scales could not adequately be captured by this approach either. The current state of the art is the multiple reference framework approach, with its increasing realism but attendant complexity and difficulty of use. Has ecohydraulics reached peak complexity? More importantly, are we now at the point where complex multiple reference framework approaches are able to capture the important processes for ecohydraulics problems, and we can start to look at ways of simplifying these approaches to make them simpler and more accessible, but without losing modelling power? Like most problems, the answer to this problem will be dependent upon the specific context in which it is asked. Above, we have observed that a single reference framework is more than adequate for some problems in ecohydraulics. Conversely, for some ecohydraulics problems, even state of the art multiple reference framework approaches may not yet capture the major driving forces for the system.

Every practitioner or student of science is anxious to make his or her mark by identifying new technologies, undiscovered processes, or new and unique relationships among variables. Using the standard model of scientific reduction one concludes that the scientific frontiers are located at the leading edges of science where scientists work at ever increasingly fine levels of detail. This could include ecohydraulic modelling approaches such as described above. However, interdisciplines, using ecohydraulics as an example, also demonstrate that a substantial number of the new frontiers occur in the areas between the established disciplines. New frontiers in these areas come from applying approaches that can no longer be considered at the leading edge of their component disciplines to new applications, and in conjunction with equivalent tools from other disciplines. Thus, the key for the future development of ecohydraulics, and other interdisciplines, is the development of effective integrating principles that allow the strength of multiple disciplines to be brought to bear on the many problems facing humanity. This last point is key, for while we are seeking to move ecohydraulics from Edison’s quadrant, we equally must maintain ecohydraulics’ foundational focus on providing practical solutions by moving to Pasteur’s quadrant. Finally, we wish to challenge our colleagues within the ecohydraulics community to continue the dialogue initiated with this paper. We believe that ecohydraulicians have the potential to develop ecohydraulics as the premier interdiscipline in science if the existing expertise in applied science can be supplemented with additional incorporation of basic research principles.

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