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Leandro Esteban M i r a n d a, Scott William R a b o r n

From zonation to connectivity: fluvial ecology paradigms of the 20th century

Mississippi Cooperative Fish and Wildlife Research Unit, P.O. Box 9691, Mississippi State,
MS 39762, USA.

e-mail: smiranda@cfr.msstate.edu, sraborn@cfr.msstate.edu

Abstract

The development of fluvial ecology during the 20th century is described, focusing both on the progression and basis of certain types of research. The original zonation paradigm was established in the late 1800s, evolved slowly early this century and supplied the foundation for early work in fluvial ecology. Zonation separated the river into well-defined longitudinal sections based most often on abiotic characteristics that dictated composition of the biotic communities. By mid-century, the number of observations that could not be adequately interpreted with the zonation paradigm began to mount, and strict zonation was called into question. Investigators argued that zones changed gradually through slow transitions, and that rivers were instead clines with ill-defined boundaries. Over a period of about 30 years, beginning around mid-century, the conceptualization of fluvial systems changed, producing a paradigm shift that opened scientific inquiry into issues not previously viewed as relevant. The new paradigm emphasized connectivity of streams; it began with longitudinal connectivity along the stream channel, and was later reformulated to include a lateral dimension that encompassed extrachannel areas (e.g. floodplain). Once outside the channel, ecologists have had difficulties deciding where to stop. Recently it is the entire basin that is defined beyond the two-dimensional longitudinal and lateral space, to include the vertical dimension extending down to bedrock. It is argued that scientific progress in fluvial ecology is both stifled and stimulated by confirmatory tendencies imposed by paradigms. A falsification approach to accelerate progress within the restraints posed by a paradigm is suggested.

Key words: zonation, paradigm, connectivity, rivers, ecology, history

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1. Introduction

Science is conducted under the umbrella of a conceptual system, defined as a mental construct that contains ideas or concepts as its parts. Such systems are often arranged in a logical fashion, are derived through induction, and can then be used to deduce patterns. The scope of a conceptual system is varied, and often one conceptual system may be part of a broader system. For example, the 'balance of nature' concept permeates through all aspects of ecology (Egerton 1973; Kingsland 1991).

The generalities afforded by ecological investigations are widely disputed, and understanding the continuity of ecology as a science is difficult. Kuhn (1970) offers one method of viewing scientific progression as a series of paradigms with various commitments. If applied to the field of fluvial ecology, Kuhn's method may help understand the pattern of adherence to a gradual turnover of conceptual systems. According to Kuhn:

- a paradigm is a conceptual system that serves as a model or pattern that directs scientific endeavor within a discipline;
- a paradigm is characterized as a network of theoretical, conceptual, instrumental and methodological commitments that guides the types of problems that scientists address, the methods they use, and even the way results from experiments are interpreted;
- the advent of a paradigm is often signaled by the formation of specialized scientist groups, publication of specialty journals and books, and the claim for a special place in academic curricula.

The scientific community that shares a common paradigm has often been "instructed" into the paradigm by reading similar textbooks and journals, and hence may also share the same rules and standards for scientific practice, a common view of problems that need solving, and how they should be approached.

Although paradigms are usually necessary for the progress of science, they limit inquiry to only those questions identified to be relevant by the paradigm. The paradigm defines what should be studied, what questions should be asked, what tools should be used, and what rules should be followed when interpreting research results. Thus, research within a paradigm involves elaborating on the concepts of the paradigm. Observations that do not fit the context of the paradigm are either not considered because the paradigm renders them irrelevant, or worse, just ignored. This approach leads to a programmatic accumulation of facts, research publications, books, and even journals that simply reverberate the paradigm, perhaps with slightly better precision, or from the perspective of a different application. The advantage of this approach is that the paradigm forces scientists to investigate parts of nature in a detail and depth that would otherwise be considered senseless (Kuhn 1970). The disadvantage is that the scientist's vision is greatly restricted.

Periodically, the adequacy of a paradigm may be challenged by observations that cannot be explained by existing concepts, leading to expansions of the paradigm, minor modifications, or occasionally substantial shifts in scientific thought. Whatever the change, the new and improved paradigm leads to a different set of commitments and a new basis for the practice within a scientific discipline. A paradigm shift is seldom just an increment to existing knowledge; often, it involves the reconstruction of earlier concepts and the re-evaluation of prior facts, and imposes entirely new questions to address.

This paper describes the development of fluvial ecology during the 20th century, focusing not only on the progression, but also on the basis behind certain types of research. The original paradigm evolved slowly early in the century, followed several rapid and often contemporary shifts in foci. Towards the closure of the century the development of a more encompassing paradigm is being experienced. The evolution of these paradigms is consistent with a shift from reductionism to holism that is evident in many fields of science. It is argued that scientific progress is stifled by confirmatory tendencies, and an approach is suggested for accelerating inquiry within the restraints posed by the paradigm.

2. Major paradigms in fluvial ecology

Two major paradigms characterize the development of fluvial ecology during the 20th century, the zonation paradigm and the connectivity paradigm. For each an attempt is made to identify the commitments that define each set of beliefs as a distinct stage in the evolution of fluvial ecology (Table I).

Table I. Major changes in commitments leading to a shift in paradigms from zonation to connectivity

Commitment	Paradigm	
	Zonation	Connectivity
Conceptual	Balance of nature	Imbalance
Theoretical	Habitats and communities exist in discrete organizations	Habitats and communities are transitional and represent a continuum
Methodological	Inquiry restricted to a longitudinal scale	Inquiry expanding a three-dimensional scale
Instrumental	Instrumentation orientated towards detecting biotic and abiotic differences among zones (e.g. flow meters, habitat measurement devices)	Application of tools for basin analysis (e.g. GIS, remote sensing)

The zonation paradigm

In the late 1800s naturalists were pursuing zonations of plants and animals. A.R. Wallace divided the world into the nearctic, neotropical, palearctic, ethiopian, oriental, and australian biogeographical zones (Berra 1981). Within North America, Merriam (1898) divided the continent into the boreal, austral, and tropical transcontinental regions, and each region was divided into life zones. Accordingly, some of the first attempts to reduce river systems into parts involved zonation (Hynes 1970; Hawkes 1975). Late last century scientists in Germany and Poland began classifying river zones according to dominant fish species such as trout (*Salmo trutta*), grayling (*Thymallus thymallus*), and barbel (*Barbus barbus*) zones (Borne 1877 and Nowicki 1889 as cited by Backiel 1964). Identification of such zones in Europe was not difficult given that the diversity of the fish fauna is low at about 20–30 species (Matthews 1998). Studies that followed early in the 20th century were focused on identifying the abiotic conditions associated with the observed animal zonation within the stream (Steinmann 1907; Shelford 1911; Thienemann 1912). The river was separated into longitudinal sections based on abiotic characteristics such as temperature, dissolved oxygen concentration, width, depth, slope, flow velocity,

substratum, and more recently, stream order. These abiotic components were considered to dictate composition of the biotic communities. Many of these historic works were reviewed by Illies, Botosaneanu (1963), Backiel (1964), and Hawkes (1975). According to Hawkes (1975), the biologists involved in this early work were trained in taxonomy and systematics, areas emphasized in the late 1800s and early 1900s. Such training might have predisposed them to classify habitats and fish assemblages into discrete zones. The idea that habitats could be depicted as discrete zones, and that biotic assemblages should follow suit, represents the distinguishing theoretical commitment of the zonation paradigm.

These early ideas supplied the foundation that generated a wealth of research that reverberated the concepts of this emerging paradigm. Most of the research was conducted in Europe and North America, but the work expanded globally and occupied much of the first half of the century. Carpenter (1928) in Wales; Huet (1949) in France; Müller (1951) and Schmitz (1955) in Germany; Illies (1953) in northeast Europe; and Sommani (1953) in Italy classified streams into zones based on fish and invertebrates, and Tansley (1939) classified river zones in the British Islands according to vegetation. In North America, Hoover (1938) in New Hampshire; Trautman (1942) in Ohio; Burton and Odum (1945) in Virginia; Gerking (1945) in Indiana; Holton (1953) in Montana; and Kuehne (1962) in Kentucky developed similar zonation schemes analogous to the stream-order system. Elsewhere in the world, zonation concepts were developed by Marlier (1953), Harrison, Elsworth (1958), and Oliff (1960) in Africa; Nikolski (1933) in Asia; Allen (1956) in New Zealand; and Kleerekoper (1955) and Illies (1964) in South America. In general, these investigators recognized more or less sharp borders between zones. Although the existence of transitional zones were described by some, transition referred exclusively to the longitudinal axis.

The concept of zonation invited longitudinal sampling to identify changes in biotic and abiotic characteristics. Various methods were developed, or adapted from other aquatic environments (Needham 1938; Welch 1948; Schwoerbel 1970) to characterize the chemical, physical, and biological differences among stream zones. The most evident development was the proliferation of habitat descriptors, formulated by biologists or borrowed from related disciplines (Horton 1945; Leopold, Maddock 1953; Strahler 1957) that are essential to zone discrimination. Researchers became aware that the rate at which biotic and abiotic characteristics changed decreased longitudinally, necessitating uneven distribution of sampling effort (Schwoerbel 1970). To interpret sampling data, graphical approaches were developed wherein sampling sites were entered on the abscissa and sampling data on the ordinate, to depict peaks and slopes of curves used to study associations relative to zones (Illies 1953). Some researchers refined this approach by treating the curves and graphs mathematically (Schmitz 1957).

Around the middle of the century the idea of strict zonation was beginning to be questioned, and several investigators began to argue that zones changed gradually through slow transitions, and that rivers were instead clines with ill-defined boundaries. Zonation knowledge often did not transfer across river systems, and zones identified for one group of organisms often did not apply to others (Maitland 1966). Attempts to make the paradigm more transferable across fluvial systems and redefine zones as real ecological entities included development of more universal zonation systems such as that of crenon, rhithron, and potamon (Illies 1962; Illies, Botosaneanu 1963). Nevertheless, the number of observations that could not be accounted for by the zonation paradigm began to mount, and enthusiasm for the explanatory and predictive power of the zonation paradigm dwindled. Also, around this time ideas about species existing along unimodal resource gradients were being advanced in the ecological literature (Hutchinson 1957; MacArthur 1957). In Italian streams, Sommani (1953) reported that sequencing of zones was irregular, with recurrent inversions of the zones identified elsewhere in Europe. Funk, Campbell (1953) reported fish assemblages changed gradually along the longitudinal axis of the Black River in Missouri (USA). Maitland (1966) argued that communities of benthic invertebrates in the River Endrick (Scotland) showed no obvious demarcation as claimed by Illies (1953) in the River Fulda (Germany). Backiel (1964) indicated that in the River Drwęca (Poland) zones changed gradually and a transitional reach may be as long as the zones themselves. By the late 1960s, the concept of distinct zones was fading. Hynes (1970), in one of the earliest textbooks focusing on stream ecology, suggested zonation was 'useful in a general descriptive way but that attempts at precise definitions of zones are of doubtful ecological value'. Maitland (1978) indicated that zonation schemes are 'rarely valid for other groups within the stream system, or even the same group in another system (.....) and thus the general theme of the change in biotic associations from source to mouth (.....) tends to be one of transition rather than zonation'.

The connectivity paradigm

Contrasting with the reductionist orientation of the zonation paradigm, the connectivity paradigm emphasizes gradients and the longitudinal, lateral, and vertical continuity of the structural and functional characteristics of riverine ecosystems, and represents a new set of theoretical commitments. Connectivity concepts extend past the water's edge, and emphasize stream interactions with their watershed including the ecotone, the floodplain, and terrestrial and aquatic environments within the entire basin. The concepts of connectivity forced an expansion in the spatial scale at which fluvial ecology patterns were considered: under the zonation paradigm, fluvial ecology focused largely on reaches, whereas the new paradigm made questions about basins more relevant (i.e. the motivation to zoom further out was incorporated).

This more holistic view of streams began to surface in the 1950s as interest in biotic production and energy flow accelerated, perhaps prompted by Lindeman's (1942) publication on trophic dynamics and Tansley's (1935) ecosystem concepts. Various researchers (Allen 1951; Odum 1957; Teal 1957; Margalef 1960; Mann 1964; King and Ball 1967) began to study biotic production and energy budgets in stream segments. These researchers considered that a stream ecosystem could be modeled through a reductionist approach by studying segments. Most of these energy budgets focused on allochthonous material primarily as fallen leaves in temperate streams, and leaves, grasses, pollen, fruits and blossoms in tropical streams (Fittkau 1964). These seminal studies led to a proliferation of stream energy budgets and associated literature in the 1960–1970s (Vannote 1963; Warren *et al.* 1964; Minshall 1967; Mann *et al.* 1972; Hall 1972; Fisher, Likens 1972; Cummins 1973; Penczak *et al.* 1976).

The study of energy budgets and material cycling through communities led to the concept of nutrient spiraling. This term described the downstream displacement of organic nutrients while they are being processed and used along the stream (Wallace *et al.* 1977; Newbold *et al.* 1981). Spiraling length units were considered a function of downstream transport rate and retention rate, that in turn was influenced by community characteristics. Spiral lengths tended to decrease in side channels and floodplain due to high physical and biological retention rates.

Studies of biotic production, energy flow, nutrient transport, and dependence on allochthonous materials accentuated the importance of land-water linkages and continuity of river reaches. The first attempt to describe the structural and functional characteristics of stream communities along the entire length of the river was the river continuum concept (Vannote *et al.* 1980). This concept postulates that river systems have an interrelated longitudinal structure prompted by a gradient of physical forces that change predictably along a river's course. The physical forces produce a continuum of hydrological and geomorphological characteristics that induce a gradient of longitudinally-linked ecological conditions from headwater to mouth. The paper by Vannote *et al.* (1980) was pivotal to the connectivity paradigm because it was the first comprehensive and explicit description of the new commitments, stating predictions and providing a new class of problems surrounding validation of the paradigm. It was not necessary for connectivity to solve all problems, just more than zonation; in fact, it is the promise of solving future problems that makes a new paradigm more attractive (Kuhn 1970). Research subsequent to Vannote *et al.* (1980) followed Kuhn's account. New problems were available, and the predictions laid out by the river continuum concept were given utmost attention. Where these predictions failed, *ad hoc* modifications were made.

The connectivity concept advanced by the new paradigm produced a successful model for unregulated temperate rivers in relatively unmodified forested watersheds. With some adjustments, the model accommodated the longitudinal differences in patterns associated with changes in climate and geology around the

world (Wais, Campos 1983; Zalewski *et al.* 1990; Garcia de Jalon *et al.* 1996; Brown *et al.* 1997; Samways, Stewart 1997), and even in heavily regulated rivers where impoundments serve as reset mechanisms in the river continuum (Ward, Stanford 1983). The development of the river continuum concept was the culmination of about a 30-year period during which the ecological value of the zonation paradigm was questioned. However, because the concept assumed a longitudinal structure of rivers, its predictions were limited to main channels and omitted extra-channel environs important in system dynamics but unconnected to the main river channel most of the year (e.g. floodplain lakes and wetlands).

A substantial modification to the connectivity paradigm was provided by the flood pulse concept (Junk *et al.* 1989). This expansion accounted for the effects of seasonal floods on both the river channel and its floodplain in unregulated river-floodplain systems. The expanded paradigm was needed because the river continuum model did not adequately account for the large influence of the floodplain on many river systems (Sedell *et al.* 1989; Bayley 1991, 1995). The flood pulse concept emphasized the importance of organic material contributions from adjacent floodplains, rather than the downstream transportation of materials stressed by the river continuum model. Thus, the flood-pulse concept expanded the connectivity paradigm by introducing a lateral dimension to fluvial systems and extending the focus of research and management beyond the main channel. This expanded connectivity paradigm has further been expanded to account for the effects of damming and river regulation in a floodplain river (Ward, Stanford 1995). Thus, the scope and precision of the current paradigm has progressed rapidly in recent years.

Once fluvial ecologists expanded outside the main channel into the floodplain, they have had difficulties deciding where to stop. Recent studies have focused on the whole basin with emphasis on the stream relation to its watershed across a wide range of scales over space and time. Many contend that the spatial extent of river ecosystems extends well beyond the channel boundary (Stanford, Ward 1988; Marmonier *et al.* 1992; Gibert *et al.* 1994). The floodplain has been defined beyond the two dimensional longitudinal and latitudinal space to include the vertical dimension extending from the river bed or floodplain surface down to the bedrock (Dahm *et al.* 1998; Ward *et al.* 1998). This hyporheic layer interacts with the interstitial layer to determine sediment structure, groundwater features, and characteristics of biotic organisms that inhabit the hyporheic layer (e.g. hypogean crustacean and amphipods (Ward *et al.* 1998)). The vertical emphasis has been primarily downward, with minimal accent on surface-air interactions.

3. Fluvial ecology reflects reductionism and holism trends in biology and ecology

Reductionism involves decomposing complex phenomena into simple components. Reductionists believe that biological systems (living organisms, ecosystems) can be decoded by studying individual parts. The reductionist view was prevalent in the 19th century, and many of the disciplines that have their

origin during this period retain various aspects of the reductionist philosophy. For instance, much of fisheries science remains reductionist, with emphases on single species and the search for individual factors (e.g. temperature, flow velocity, water depth) that may be of commanding importance to each species. The reductionist approach provides high understanding and perhaps controllability over very small parts of the ecosystem, but minimal realism. In the middle of the 20th century holism began to compete with reductionism, as biologists and ecologists began to realize that the interactions among the parts that made up a biological system were often what dictated the characteristics of the system (Rigler, Peters 1995). Conversely, the holistic approach provides relatively low understanding and controllability over small parts of the ecosystem, but greater realism.

The paradigm shift observed in fluvial ecology has reflected these developments, which in turn have been driven by changes in societal convictions and needs. Ecology had its beginnings in the late 19th century, although it did not achieve high visibility until the mid-20th century. Its roots have been argued, but it is generally recognized that it originated, at least in part, from the efforts of 19th century naturalists to describe the structure associated with the balance of nature (Egerton 1977; McIntosh 1988). The balance concept was presumably linked to the strong religious convictions of societies, that often involved the existence of equilibrium and symmetry provided by a master plan devised by a higher being (Kingsland 1991).

Much of these early efforts in ecology involved classification of phenomena into distinct categories, because the categories implied order, and order was prescribed by the balance of nature paradigm. The belief that categories existed drove early ecologists to develop a host of classifications and the methodologies needed to distinguish groups (whether they existed or not); for example, botanists in the 19th century were involved with classifying flora according to geographical coenoses or zones (Mueller-Dombois, Ellenberg 1974). Likewise, early limnologists emphasized classification of water bodies based on physical characteristics; they identified various vertical and horizontal zones in lakes, and developed lake typologies based on organic content, benthic and fish assemblages, phytoplankton characteristics, trophic status, and others (Rodhe 1975). Formative schools of thought in ecology were those advocated by Clements (1905) and Gleason (1926). Early on, plant ecologists were engaged in a lively controversy as to whether terrestrial plant communities should be thought of as discrete units (Clements 1905), or whether populations respond independently to environmental gradients such that communities overlap in continuum and recognition of distinct units is arbitrary (Gleason 1926). It seems the Clementsian view was more prevalent in the first half of the 20th century concurrent with zonation; recently, the Gleasonian view has emerged into the spotlight, paralleling the switch to connectivity.

The shift in thinking in modern ecology has been associated with the ideas of scale, disequilibrium, and heterogeneity. The foci of ecology, including

fluvial ecology, are in transition from discrete to connected, from single-scale to hierarchical linkages, from determinism to stochasticity, from balance to imbalance, and from homogeneity to heterogeneity (Wu, Loucks 1995). Non-equilibrium theories of community structure, including disturbance and patch dynamics (Reice 1994), are being incorporated into ecology. These changes are affecting the way in which aquatic resources are perceived, studied and managed. Stability in contemporary ecological thought may only exist as an average condition in a large spatial scale (Reice 1994), and even that is being questioned. Relatively new fields of ecology are emerging into the foreground, such as landscape ecology and conservation biology, with their own specialized language and flagship journals. These fields emphasize the importance of spatial context and connectedness in research and management, and have developed distinct theoretical, conceptual, instrumental and methodological commitments (Galindo-Leal, Bunnell 1995).

Ecology is for the most part shifting from a focus on discrete components of a system (e.g. species, habitat units), to a focus on large, dynamic systems (e.g. patch mosaics, metapopulations). Central to this shift in paradigm is the concept of ecosystem management. The term is increasingly being used by scientists, managers, policy makers and the public, but not always with the same meaning. This disagreement reflects a confusion often evident during a period of paradigm shift (Kuhn 1970). The confusion is attributed to the fact that scientists may be at various levels of conversion into the new paradigm (although some may never convert), and are thus operating from different perceptions and making assessments at different scales.

During the 20th century human populations have increased dramatically and humans have acquired substantial power to alter nature. Together, these events have led to large-scale changes in environment, as well as broad regional and global environmental disasters. Some examples include deforestation, draining of wetlands, eutrophication of aquatic systems, pollution, acid rain, and global warming. Societal awareness of this systematic destruction of the environment and its effect on the biota was boosted in the USA just after mid-century by Carson (1962), initiating what has come to be known as the environmental revolution. Since then, society began to demand from science solutions to broad environmental issues, forcing ecologists to work more and more on landscapes and to identify patterns applicable across landscapes. Analogously, within the field of fluvial ecology large-scale alterations of river systems through damming, construction of embankments, and watershed modification were the catalysts that prompted the connectivity paradigm.

4. Scientific progress is stifled by confirmatory tendencies

Two kinds of scientific progress can be identified – within a paradigm and between paradigms. Within a paradigm, progress represents solving the problems identified by the paradigm as relevant. For instance, in fluvial ecology the connectivity paradigm identifies the role of the riparian zone on suspended

sediments, or distribution of invertebrates in backwaters, as problems worth solving, and developing solutions to these problems (labeled 'normal science' by Kuhn 1970) would represent progress.

Science is highly cumulative within the paradigm, and progress towards solving the problems identified as relevant may be considered linear. The paradigm defines and confines the research that must be conducted, and generally the results are not unexpected. Between paradigms, the definition of progress is more controversial. According to Kuhn (1970), paradigm shifts result in a change of focus; thus, problems addressed by the old paradigm become irrelevant under the new paradigm. When a paradigm is discarded, the scientific community questions most of the literature in which the paradigm had been embodied. From this perspective, Kuhn (1970) questioned whether science actually moves steadily ahead, or whether it progresses at all. The authors are of the view that if a new paradigm can explain and predict nature better than the old paradigm, then there is progress between paradigms. For example, connectivity seems to represent progress over zonation because it is potentially able to make predictions about the effect of an impoundment (or other modification of the basin, in or out of the channel) in the upper basin on, say, nutrient levels and fish assemblages in the lower basin.

Progress within a paradigm is needed to achieve progress between paradigms. Research within the paradigm does not aim at developing new information outside the realm of the paradigm; instead researchers work to enhance the scope and precision with which the paradigm may be applied. Paradigmatic research provides the environment for generating the information that can lead to discarding the paradigm, and potentially make progress between paradigms. According to Kuhn (1970) advances within the paradigm increase the agreement between theory and observation; thereby the researcher often knows with precision what results should be expected. Unexpected results (labeled 'anomalies' by Kuhn 1970) can occur only against the backdrop of the paradigm. The more refined the paradigm is, the more definitive its expectations are, and the easier it is to identify anomalies. Therefore, the paradigm provides the environment for conducting science, the mechanism for recognizing its own deficiencies, and sets up the stage for progress between paradigms.

In practice, anomalies are difficult to identify because scientists often exhibit a tendency to confirm their paradigm. Contradictions of the paradigm are often discounted as error in the experiment, measurement error, or random variance. If anomalies are recognized as a legitimate contradiction, the paradigm may be modified just enough to accommodate the new observation (e.g. expansion of river continuum concept to accommodate the flood pulse concept). Therefore, scientific progress between paradigms is not only enhanced by working within a paradigm that provides direction, but is also stifled by severely blinding researchers to alternative conceptions.

Ecology suffers from innate variability across spatial and temporal scales. Consequently, theory justification, which ends in confirmation or refutation, often seems arbitrary. There is a propensity to confirm what others have done in any discipline, but perhaps this bias is even more flagrant in ecology where theories are less universal. Ecology is a 'soft' science and may not hold to the standards required for the deductive-nomological argument. At the same time, it is necessary to guard against unwarranted inductively-supported confirmation and be aware that there is a tendency to select evidence in support of in-vogue theories. Such redundancy delays progress and wastes limited funds.

How may confirmatory tendencies be guarded against? A dramatic change in attitude is needed. Progress in fluvial ecology may be accelerated through application of a falsification approach (Popper 1972). Falsification would require that experiments, whether controlled by a researcher or dispensed by mother nature, be viewed as tests of the existing paradigm, as efforts to find anomalies rather than confirmatory evidence, and as attempts to find flaws in the paradigm rather than to validate it. Falsification of hypotheses necessitate construction of alternative theories and hypotheses, alternative even to those that seem irrefutable. In constructing alternative theories and hypotheses, researchers must continually be aware that the view of fluvial systems is shaped unconsciously by concepts that are taken for granted, although they are often likely to be false. Understanding the nature of paradigmatic science and how falsification should be used to combat redundancy during confirmation is essential if research is to be justified as contributing to fluvial ecology.

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