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## Creativity, idea generation, and the functional morphology of streams

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*Abstract.* Stream research has contributed only modestly to general ecological theory. Moreover, the rate of generation of new ideas in stream ecology may have slowed recently. These shortcomings might be remedied by a more deliberate effort to generate new, creative ideas about streams that will enhance their use in developing general theory. The creative process has been thoroughly studied by psychologists and, while the field is still in flux, most cognitive psychologists agree that juxtaposition of disparate concepts or observations can stimulate new ideas. How this technique might enhance stream ecology is illustrated with an analogy between functional morphology and stream ecology. Definition of form and function in streams is required to develop this analogy and a hierarchical, scale-dependent approach is essential. The effect of structure and configuration of stream channels on their functioning is a promising research area that can be applied at several scales. Parallels with landscape ecology are strong. Extending this analogy to larger scales reminds us that streams are, in essence, branched systems; however, little research has been done on the ecological consequences of branching patterns in streams and rivers. Combination of this branched image with other surface and subsurface water bodies leads to an even broader view of streams as planar systems, intimately connecting terrestrial and aquatic ecosystems along flowpaths. This exploration of ideas about stream shape and its functional consequences suggests several opportunities for stream ecology to contribute to general ecological theory. More importantly, this effort suggests that the process of idea generation is straightforward, accessible, and beneficial for both science and scientist.

*Key words:* creativity, stream morphology, ecosystem structure and function, stream network.

Stream ecology is a habitat-defined rather than theory-defined subdiscipline of ecology. Stream enthusiasts share their allegiance to stream ecology with other disciplines such as biogeochemistry, evolutionary genetics, behavioral ecology, and biogeography. Habitat-defined disciplines lack conceptual cohesiveness and are more engaged in adapting theory developed elsewhere to a specific situation, in this case, to running waters. If new ideas are generated through habitat studies, they are quickly appropriated by more conceptually oriented related disciplines. While progress in stream ecology has been substantial over the past 5 decades or so (Minshall 1988), much of this success has been derivative; that is, it has resulted from conceptual and methodological advances in allied sciences. Generation of new ideas about streams from work in streams has been modest, especially considering the increase in the number of practitioners of the field, as shown by the almost 50% increase in membership in the North American Benthological Society over the last decade (Fisher 1991).

Research and publication in stream ecology proceed unabated. In David Allan's (1995) new book on stream ecology, 83% of the 1200 refer-

ences were published since Hynes's (1970) classic volume. The conceptual landscape of the science has changed as well (Fisher 1995); however, little of this is incorporated in the major textbooks of ecology. Neither "river" nor "stream" appears in the 1000-entry index of Robert Ricklefs's (1990) widely adopted textbook of ecology. Papers central to stream ecology are scarcely mentioned. For example, faculty and students of stream ecology at Arizona State University and at Virginia Tech generated a combined list of 50 published papers in stream ecology which they judged to be classics in the field. Only 6 of these are included among the 2200 references cited by Ricklefs (1990). This is no indictment of Ricklefs, since the pattern is repeated in many texts of general ecology. The ideas that have been generated by stream studies have not been widely adopted, perhaps because of their habitat specificity or their lack of explicit connection with general ecological theory.

Idea generation is an important issue in graduate education as well. Students embarking on a career in ecology are much more apprehensive about their ability to generate new, significant ideas than they are about mastering the rapidly changing technological tools of the field (Fisher

1991). While the reverse is true of faculty mentors, those of us involved with students have few concrete answers to their urgent questions: What's worth doing? How can I make a significant contribution? Is this a good idea? Our common advice to "let your curiosity lead you" is lame indeed if offered in a conceptual vacuum. What's worth being curious about?

The problem then is to consider whether new ideas about streams can be generated at a greater rate and in a more stimulating form. My objective in this paper is to discuss some of what we know about where new ideas come from; that is, creativity in science. I shall then apply 2 techniques, conceptual juxtaposition and analogy, to stream ecology to illustrate how novel ideas and enticing research problems might be generated. The goal of this exercise is to generate ideas from streams, about streams, and for streams, and also ideas that are of eminent interest to general ecology. I shall argue that idea generation is neither mysterious nor inaccessible to the average researcher. On the contrary, creativity can be analyzed, enhanced, and deliberately applied just as any other research tool can be.

### Disciplinary progress

Platt (1964) posed several hypotheses to explain why some scientific fields are more productive than others. Is productivity traceable to better funding, more intelligent people, better training, more tractable problems, or relevant technological breakthroughs? Without examining the proposed alternatives, Platt concluded that productive fields are marked by traditions of clearer, better organized thinking. Better organized thinking involves clear questions, use of logical syllogisms, multiple hypotheses, and well-planned experiments designed to reject incorrect hypotheses. While Platt's hypothesis applies well to fields such as chemistry and genetics, ecology is a newer field, judged immature by Loehle (1987). Questions pursued in immature sciences may not be sufficiently honed to respond productively to the strict hypothetico-deductive approach prescribed by Platt (1964). Ecology, including stream ecology, is often concerned with pattern recognition, problem identification, and phenomenology. While experimentation has served ecology well, a wider range of epistemological techniques may be ap-

propriate when the field is still immersed in concept generation and early stages of theory development (Pickett et al. 1994). Adroitness at puzzle solving using sophisticated statistical techniques and experimental design may in fact deter theoretical breakthroughs because the universe to which these tools can be applied is so limiting. Moreover, confirmatory techniques may deserve equal footing with the falsification (hypothesis rejection) techniques central to Platt (1964) and other logical positivists (e.g., Popper 1959; see also Pickett et al. 1994).

As ecology is involved in early stages of theory development, what kinds of techniques can be used to better link observations with conceptual constructs or concepts with each other? In particular, how can stream ecology itself advance and contribute to a greater extent to ecology as a whole? What kinds of questions of broad ecological importance are stream ecologists best positioned to answer? What new paradigms await development? To answer these questions requires some understanding of where ideas come from. How does the creative process work?

### Individual creativity in science

The literature on creativity is voluminous and ranges from the carefully controlled experiments of cognitive psychologists to new-age, self-help treatises. This material is not easily accessed by ecologists, and therefore I shall summarize a few basic elements here.

Creativity is defined as the production of novel, socially valued products (Mumford and Gustafson 1988). In science, major creative products involve an integration and reorganization of cognitive structures, i.e., concepts, interpretations, theories—ways of thinking about things. Minor creative products result from an application of existing cognitive structures to new observations or locations (Mumford and Gustafson 1988). The River Continuum Concept (RCC; Vannote et al. 1980) is a major creative product. It resulted from the integration of several different, existing concepts of organic matter processing, geomorphology, and biological productivity, among others. The hundreds of subsequent papers applying the RCC or parts of it in every imaginable situation are, at best, minor creative products, although they may be excel-

lent examples of the application of scientific inference.

Wallace (1992) commented on the ontogeny of ideas in stream ecology as illustrated by the several-year time lag between the first appearance of an idea at a NABS meeting and the deluge of abstracts documenting it in detail. Insofar as the annual meeting program mirrors scientific activity in a field, the bulk of research creativity in stream ecology is minor, as defined above. This time course of idea generation, development, and recession is probably general for ecology, and perhaps for all of science. Meetings of scientific societies are marvelous opportunities to generate ideas if paper sessions are broadly, even randomly, sampled. However, most attendees focus on sessions in their specialties and seek new ways to elaborate old ideas. This subverts the creative process by starving it of variety. Conservative methods applied to existing ideas do not generate much innovation (Nickles 1992).

Creativity does not require genius. High intelligence is not correlated with creative ability (MacKinnon 1970). There may be a genetic component, but there is an equally important cultural influence. Creative people tend to seek out and be sought out by creative people. In science, the mentor-apprentice relationship is paramount. Nobel laureates tend to beget Nobel laureates (Zuckerman 1974). While genius is not required, education is. Conventional learning is vital to the synthesis, in that it provides the elements to be synthesized. Creation generates a new structure of known parts. It is the structure, the connections, the configuration that is new, not the parts. Available evidence supports the view that creativity is an acquired characteristic.

The actual process of creation has been divided into 4 discrete stages: preparation, incubation, illumination, and verification (Poincaré 1914, Wallas 1926). Preparation refers to gaining an understanding of the elements that might be synthesized. Incubation is a little-understood process during which information is apparently processed without conscious awareness. Illumination involves the point of appearance of the nascent construct. It is usually of sudden onset, a "Eureka" or "Ah-ha" experience with few preceding clues. It apparently occurs by intuition, which is reasoning free, as a flash of illumination (Metcalf and Wiebe 1987). It is the immediate apprehension of an object without the in-

tervention of reasoning (Bowers et al. 1990), although there is ample evidence from recent studies of the cognitive unconscious (Kihlstrom 1987) that non-conscious mental structures contribute to creativity. These are not hardwired, but result from past experience, long since rendered unconscious (Kihlstrom 1987). Verification involves refinement, logical testing, and elaboration of the new synthesis in a form amenable to comparison with existing structures.

While this process may still seem mysterious to the natural scientist, it seems to me that there are several elements of creativity that could be nurtured. A sound, broad education extending into related disciplines is requisite (Simonton 1984). Varied experiential activity should also contribute. An understanding of the structure of existing theory should provide skeletal frameworks for new possible constructs. Finally, sufficient self-awareness to recognize intuition and its products as nascent ideas and an intellectual environment where new ideas are welcomed and constructively discussed are essential. Such an environment need not be restricted to the laboratories of Nobel Laureates.

Given this sketch of the workings of the creative mind, I propose that deliberate juxtaposition of distantly related observations or ideas should stimulate creativity. This can be done by broad formal study, use of randomly assembled Venn diagrams to superimpose ideas, simultaneous projection of disparate photographic images (Shepard 1978), or other techniques to explore connections among the seemingly dissimilar. Creative people have "flat associative hierarchies", meaning that they range widely in word-association tests (Mednick 1962). Making deliberately broad connections can be practiced. Divergent thinking—attempts to devise multiple (not necessarily all equally plausible) solutions to a given problem—can foster creativity (Mumford and Gustavson 1988). Analogies and metaphors can lend productive insights by comparison, if they are constructed with care (Mumford and Gustavson 1988).

Finally, some psychologists believe spatial visual images are more conducive to creative synthesis than verbal images, i.e., language (Intons-Peterson 1993). Spatial images are free of the channeling and cuing inherent in words and are more readily manipulated than language. Language tends to bias subjects toward particular interpretations (Shepard 1978). Ecology is rich

in spatial images—photographs, diagrams, model schematics, maps, graphs, satellite images—and creativity may be facilitated by their increased use. On the other hand, images can also lead us astray if they are not carefully selected. Initial interpretation of an image can affect its ultimate interpretation in that it may exclude certain important attributes (Chambers and Reisberg 1992). I shall return later to this point when considering abstract images of streams and rivers.

My point is that the creative process is accessible to everyone. It can be understood, taught, enhanced, practiced, developed, and valued. However, in most research labs, there is no deliberate effort to develop creativity. This is not to say that creativity does not occur in many labs, only that it could be significantly enhanced if it were more systematically addressed.

#### The Venn diagram as a creative tool

Creativity involves new ways of assembling the familiar. Several tools can be enlisted in this effort. A Venn diagram consists of partially overlapping circles, which can be used to deliberately juxtapose disparate elements. Mathematicians use Venn diagrams to illustrate set theory. I have used Venn diagrams in teaching stream ecology to force students to juxtapose 3 recent research papers, selected at random, and to explore new research questions implicit at intersections, a procedure that produces stimulating ideas and stimulated students. Venn diagrams can be examined in an unweighted fashion; however, it is often more efficient to allow the central discipline (e.g., stream ecology) to generate questions and to seek answers in zones of overlap with juxtaposed elements.

In the example I shall use, the circles contain the subdisciplines stream ecology, geomorphology, and evolutionary ecology (Fig. 1). An examination of the diagram, especially its zones of overlap, could reveal a host of relationships. For purposes of this paper, I shall explore one product of the juxtaposition, which I shall refer to as functional morphology of streams. Evolutionary ecologists are interested in organismal body form and shape and how this shape relates to the environment in a functional sense. This discipline is functional morphology and is properly restricted to the organism level of organization. But streams have shapes too, and

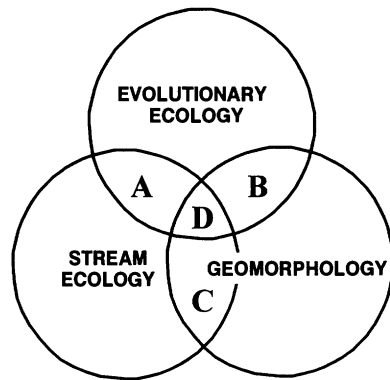


FIG. 1. Venn diagram juxtaposing geomorphology, evolutionary ecology, and stream ecology. As described in the text, consideration of overlapping ideas in zone D helps organize thoughts about geomorphic structure in streams and its influence on stream function.

the discipline of geomorphology is concerned with mechanical, historic, and dynamic determinants of stream shape. What more could we learn about stream shape and function by analogy with functional morphology of organisms?

A note of warning is in order here. The history of ecosystem science is replete with examples of confusion driven by over-extended analogy and misapplied metaphor (Hagen 1992). Clements's (1905) superorganism concept of communities, Hutchinson's (1940) physiology of ecosystems, and Odum's (1969) "strategy of ecosystem development" are prime examples. Organismal analogies in particular have caused no end of troubles for community and ecosystem ecologists over the past several decades. Some of these problems have been based on a misunderstanding of the central role of natural selection at the level of the individual. Moreover, unit-ecosystems are not themselves subject to natural selection; thus, both their organization and feedback systems result from quite different forces. Other problems are semantic. Terms such as function, adaptation, development, and efficiency have specific, value-laden meanings in organismal biology. Their cavalier use by community and ecosystem ecologists raises red flags in the minds of evolutionists that block an open exchange of ideas. The purpose of my discourse is not to seek homology where none exists. I shall not generate a new superorganism model for ecosystems. Rather, I am interested in what stream ecologists can learn from the way

functional morphologists think about organisms.

### Streams and stream ecology

To explore the analogy between stream ecology and functional morphology, it is first necessary to limit the discipline of stream ecology and to define the notions of structure and function. There are 2 types of practicing stream ecologists: those concerned with ecology "in streams" and those doing ecology "of streams". "In stream" ecologists use the stream as an arena in which to do ecological research. Questions are of general application and answers could be sought just as well in other environments. Behavioral ecology, population biology, studies of competition or predation, food web analysis, and organic matter processing studies are examples of "in stream" ecology. Many important contributions to our understanding of streams have come from this endeavor, and ecology as a whole is richer for it; but this approach to streams is not relevant to the present analysis.

Ecology "of streams" is ecosystem science. Questions pursued focus on how streams or parts of them are structured and on how they function. Structure (=stream morphology) refers to the size and shape of patches, variously defined, and to the configuration among patches of the same or different types. Structure consists of the physical-chemical template and superimposed biota. Structure can be resolved in several currencies (substrate type, hydrodynamics, chemistry, morphometry—anything that can yield a spatial map) but relevant structural elements will vary as a function of scale. Hierarchical models have been especially useful in describing structure in streams (Frissell et al. 1986, Gregory et al. 1991).

Definition of function also relies on a hierarchical model. J. S. Rowe (1966) suggested that 2 functional questions are askable about living systems, including ecosystems: "How does it function?" and "What is its function?". The 1st question is physiological and considers how the various parts of the system contribute to some overall dynamic. The 2nd asks about the role played by the system in the larger context of which it is a part; that is, its ecology, according to Rowe (1966). Thus, a thorough definition of function spans 3 hierarchical levels. Note that to the evolutionist, function connotes design and

natural selection is the architect (Williams 1966). In ecosystem ecology, function simply refers to what a system does (Grimm 1993) without implying design, purpose, or feedback control.

But what do streams do? What is the overall dynamic to which the parts contribute? And how is this overall dynamic related to the larger whole, the landscape, in which streams are embedded? The essence of streams (their overall dynamic) is embodied in transport, transformation, and connectivity. Streams are elongate ecosystems that transect and erode diverse terrestrial landscapes. The medium (water) and its dissolved and suspended load move rapidly in a highly predictable, spatially oriented manner. Materials in transport are processed, changed, recombined, temporarily stored, and reentrained. Materials move about in all ecosystems but streams epitomize this process in terms of both rate and degree of spatial orientation. Transport, transformation, and connectivity are also central to what streams do in the larger landscape and all of these are sensitive to ecosystem structure. I shall therefore define stream function in terms of both ecosystem physiology and ecosystem ecology (*sensu* Rowe 1966) for purposes of the analogy between stream and organismal function. Obviously, other conceptual constructs could be derived and other definitions devised to explore additional fruitful juxtapositions in a search for new ideas. The beauty of this approach is that it is unlimited and can be tailored variously. Mine is just one path.

### Functional morphology: organisms and ecosystems

Functional morphology is a field of biology that attempts to understand the evolution of form and structure in organisms. It is broadly concerned with making connections between how organisms are constructed and the ecological and evolutionary consequences of that design. Several levels of analysis can be employed (Table 1, Reilly and Wainwright 1994) but the first step is always based on **morphology**. Morphology refers to structure, anatomy, or shape of an organism or some part of an organism, e.g., a bird's beak, a mammal's teeth, or a fish's body shape. The **function** of this structure is then related to a **natural behavior**, e.g., food handling or locomotion. **Performance capacity** defines the **fundamental niche** with respect to

TABLE 1. Analogy between the levels of analysis used in the studies of the functional morphology of organisms and those which might be adapted to streams. The basic conceptual structure is provided by organismal studies (Reilly and Wainwright 1994). Stream ecosystems are conceptually juxtaposed with this scheme in an attempt to generate a novel way of perceiving the relationship between structure and function in ecosystems. The terms morphology and function can be applied to ecosystems if definitions are altered somewhat. Fitness and niche apply only to organisms, although loosely parallel ideas can be generated for ecosystems.

Level of analysis	Organisms	Ecosystems
Fitness	Natural selection (feedback on morphology)	No natural selection; (weak performance feedbacks on morphology via physical laws; geomorphology)
Realized niche	Actual performance (actual resource use)	Actual performance (actual function)
Fundamental niche	Performance capacity (potential resource use)	Performance capacity (potential function)
Function (of a structure)	How is structure used in natural behavior?	How does structure (holon) influence function?
Morphology	Anatomy, form, shape (several levels of analysis possible)	Structure, form, shape, configuration (at several hierarchical levels)

the pertinent resource or activity and is usually determined in a biomechanical sense in the laboratory or in the field under optimal conditions. For example, swimming speed in still water at optimal temperature, or seed handling rate when seeds are present in excess and competitors or predators are absent, measure performance capacity. Potential resource use is modified in nature by environmental conditions (e.g., the presence of competitors or suboptimal ambient temperature), thus defining the **realized niche**. It is this **actual performance** that is selected for or against in the currency of **fitness**. **Natural selection** then feeds back on morphology through differential fitness. To the extent that form (structure, morphology) confers fitness in the existing environment (i.e., is an adaptation), structure is modified from generation to generation. The main research questions of organismal functional morphology are 1) How does a given design function? (e.g., biomechanics), 2) What ecological traits can be inferred from morphological traits? (ecology) and 3) How did the organism come to have that design? (evolution) (Reilly and Wainwright 1994).

It is this scheme with which I shall juxtapose stream ecology in search of insight through analogy (Table 1). Depending on the scale at which they are viewed, streams have **morphology** (structure); for example, sediment size distribution; sand bar size and location; pool-riffle ratio; size, position, and composition of organic

matter accumulations. As with organisms, the function of a structure is its contribution to a **natural behavior**. As defined earlier, at the ecosystem level (ecology "of streams"), material transport, transformation and retention are essential natural behaviors, or **functions**. Analogizing from functional morphology of organisms, we might ask how ecosystem structure influences ecosystem function. The effect of structure on function can be described as **performance capacity** (potential function); for example, the maximum rate at which nutrients are retained or the shortest sustainable spiraling length under optimal conditions is a measure of performance capacity. **Actual performance** is reflected by the same measures under suboptimal conditions, for example at high flow, in the presence of toxic substances, or when suspended sediments are elevated. The difference between actual performance and performance capacity may be of some management significance, as an index of ecosystem health, as discussed by Meyer (1997). I have avoided using "niche" to describe performance because the analogy between organismal resource use and ecosystem nutrient retention efficiency is limited, but the analogy has prompted us to think about what streams actually do in the larger landscape and how their structure constrains this functioning over a range of environmental conditions. In this sense, the analogy may lend

insight and help generate new ways of looking at streams.

To this point I have avoided extending the metaphor to include **natural selection**. The ecosystem has no fitness and is not a unit of selection. However, if we dare to explore the fringe of the analogy, we see that the essence of evolution is feedback modification of structure via performance. While fitness per se is unavailable to ecosystems, the larger question is, Are there **performance feedbacks** on structure in ecosystems? Does a retentive system change in shape or configuration by virtue of its retentiveness? These feedback mechanisms would likely be geomorphological, and based on physical principles; however, biology could play a role. For example, nutrient retentive systems may increase growth of macrophytes, which accumulate sediments leading to increased braiding or meandering, both of which increase stream surface area per unit valley length, which enhances nutrient retention. Morphology (structure) would thus change in response to performance (function). Changes in configuration driven by performance feedbacks may be directional and predictable and occur between resetting disturbance events (e.g., flash floods) or may follow a seasonal trajectory.

As I warned at the outset, the use of organismal analogies in ecosystem science is dangerous and will be unsettling to some. The point, however, is to juxtapose a well-developed cognitive structure—provided by functional morphology—with stream ecology, to see if new ways of thinking about streams emerge. The intent is not to search for homologies between organisms and ecosystems; I doubt any exist. An exercise like this one makes us define more clearly what stream function is, to think about structure in this context, to consider how structure might influence function in streams, and to entertain the possibility that feedback between structure and function exists.

There are convergent paths to this conceptual point. For example landscape ecology deals with both the cause of patterns in space and the consequences of those patterns for processes such as the spread of fire, migration of animals, or production of biogenic gases (Turner 1989). Patch-dynamic approaches have been useful in stream ecology (Pringle et al. 1988). Their logical development could also achieve this same conceptual end. Functional morphology may

more strongly encourage us to think about essential functioning in streams, actual and potential performance, feedback controls, and temporal trajectories of configuration. In contrast, both landscape ecology and patch dynamics are strongly habitat-oriented; that is, they would not as easily stimulate our separation of “in-stream” from “of-stream” perspectives. Still, the point is that new ideas come from juxtaposition of disparate elements. It is counterproductive to prescribe at the outset what elements should be juxtaposed.

#### **Stream shape and configuration effects at different hierarchical levels**

Testing the utility of an idea is the final, verification step of the creative process (Wallas 1926). If functional morphology of streams is a fruitful idea, it might be useful to explore a few examples of its application. The effect of form on function depends, in detail, on the hierarchical level at which we view the stream. If the stream is decomposed hierarchically, the structural elements (holons) at each level interact. This interaction provides the mechanism for function at that level (O'Neill et al. 1986, Pickett et al. 1989). Structure, though, consists of more than the identity of structural elements; it also includes their size, orientation, configuration, and relative position. For example, configuration takes into account not just particle size distribution of stream sediments, but how particles are mixed, stratified, or packed. Particle configuration in turn will influence hydraulic conductivity and the location of upwelling and downwelling zones. Location and size of upwelling and downwelling zones influence spatial pattern and rate of algal growth (Valett et al. 1994). Algal growth rate is an important determinant of nitrogen transformation and retention, which in turn influence spiraling length (Grimm 1987).

At the reach scale, configuration can be described by the organization of pool, riffle, and run patches. Here again, size and relative number are insufficient. The sequence of patches may be important to function as well. A riffle-run-pool ordering sequence may function differently from a run-riffle-pool sequence in terms of, for example, organic matter processing, P/R ratio, or organismal flux via drift.

Nutrient retention in reaches of desert streams of southwestern USA depends on con-



figuration of sand bars. For example, as water moves slowly through sand bars in Arizona desert streams, dissolved nitrate increases asymptotically as a result of bacterial nitrification. Because this relationship is curvilinear, a fixed amount of sand will generate more nitrate if it is distributed in several small sand bars rather than in a few large one (Holmes 1995). As the stream dries in summer, channel configuration shifts from braided to meandering, and mean sand bar size increases. Nitrogen limits primary production in these streams, and thus algal growth is stimulated at outwelling zones where water emerges from sand bars and rejoins surface flow. More nitrogen is retained by algae at sand bar edges in spring than summer as a result of this configuration change.

An exhaustive survey of shape and configuration effects on transport and transformation in stream channels is beyond the scope of this paper. However, it is a stimulating challenge to think of the many ways stream shape at different scales can influence stream function. Some examples can be gleaned from the literature; others remain to be discovered. As patterns emerge, new ideas can be generated to explain scale-dependent relationships in space and time and to discover the array of factors that control these patterns.

### The "true" configuration of streams

As stated earlier, cognitive psychologists have suggested that spatial images (drawings and diagrams) may provide more fertile raw material for idea generation than language because images are more straightforward and free of distracting, misleading connotation. But spatial visualizations can limit creative activity as well if images are faulty (Chambers and Reisberg 1992). Streams can be imagined abstractly and depicted graphically—the literature is full of such images. Do these images, these ideograms, support creativity in stream ecology or does their content limit how we think about streams?

I recently asked a group of graduate students and post docs in stream ecology to draw a picture of a stream. I allowed only one minute for this activity (to preclude creative thought). I later repeated this activity with a group of undergraduate ecology students with similar results. The images were uniformly of a line, sometimes wavy. Heterogeneity was incorporated. The ri-

parian zone and organisms were often included. One student drew the stream only in cross section. Scales were similar. Students drew what they might see standing on a stream bank taking a photograph; I would have done the same. David Allan begins his recent book (Allan 1995) on stream ecology with a similar representation:

"Our first impressions, when we gaze upon a river, are of the strength of the current, the dimensions of the channel, and perhaps the boulders in the stream bed or the shape of the banks."

This common view of streams acknowledges their structural heterogeneity, their morphology, their flow dynamics. But our mental images of streams tend to converge on a common scale and these images are almost invariably linear.

I was prompted to perform the drawing exercise after perusing a popular book of Elliot Porter's photographs of nature. The book is entitled "Nature's chaos" and the slim accompanying text is written by James Gleick (Porter and Gleick 1990), who has written more extensively on chaos theory elsewhere (Gleick 1987). One passage came as a revelation to me:

"Imagine a river's basic shape. Inevitably and universally we imagine a line, drawn with some curve or wiggle. Rivers flow, meandering, according to our sense of the river's essential form—in a line.

"It is not so. Our imagination misled us. In reality, a river's basic shape—and it does have a basic shape, repeated wherever nature empties the land of water—is not a line, but a tree. A river is, in essence, a thing that branches." (p. 11–12).

### Streams as branched systems

Now every stream ecologist actually knows that streams are branched. But when you examine what stream ecologists do, there is little connection between research activity and the stream's basic, essential shape. Over the past quarter century, the major paradigms and research foci in stream ecology have been based upon a linear ideogram—an image which is at best incomplete and at worst, incorrect. Organic matter budgets have been reach specific and thus linear (Fisher and Likens 1973). Tributaries represent point inputs and are included in bud-

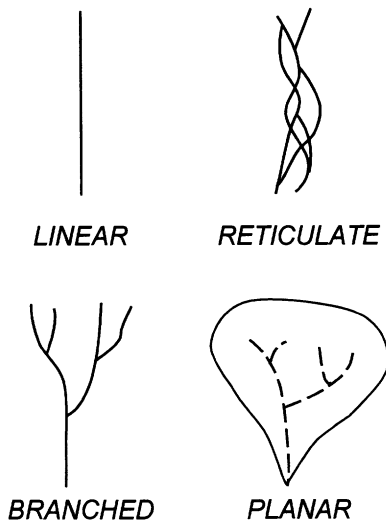


FIG. 2. Alternative map-view ideograms that can be used to organize ideas about the shape of streams. Linear: the simplest perception focusing on the flowing wetted perimeter. Reticulate: acknowledging local exchanges along flowpaths within the stream/riparian-corridor ecosystem. Branched: the basic structure of streams. Planar: for a given catchment, all surface and subsurface water including shallow and deep groundwater as integral parts of the stream ecosystem.

gets, but their location, number, and distribution are not explicitly considered. The RCC is in fact a linear model (Vannote et al. 1980). Although it deals with changes from headwaters to larger order rivers, the model does not explicitly incorporate the effects of branching patterns, numbers of tributaries in each order, and junction effects. The well-known RCC diagram is shaped like a boojum tree with a single branch, even though in the first published account of the RCC (Sandusky River Symposium) this one branch had not yet appeared (Cummins 1975). The nutrient spiraling theory (Newbold et al. 1982) is linear by definition. Reaches selected for spiraling measurements may not include accrual of any kind—certainly not tributaries (Stream Solute Workshop 1990). Recent work on flowpaths—hyporheic exchange, lateral excursions into sand bars and riparian zones, floodplain exchanges; all with linked return flows—impose a reticulate element on this linear image (Fig. 2), but the basic shape remains a line.

Although linear elements may be scaled up to the drainage-net scale, assembly rules are badly needed and are invariably missing. Scaling up

of order-specific measurements is usually done empirically or by using data from an array of orders, but from separate catchments (e.g., metabolism of the Matamek River system; Naiman 1983). The RCC group has incorporated link magnitude as a variable to consider the influence of tributaries of various sizes on invertebrates and organic matter of (linear) main river channels (Bruns et al. 1984, Minshall et al. 1985). Stanley (1993) incorporated tributaries in her conceptual model of drying effects at the basin scale; however, branching pattern was not explicitly treated as a structural variable.

What is needed is an explicit consideration of branching pattern—the shape of streams—as an independent variable to which various functional attributes (e.g., nutrient retention efficiency, organic matter transport) are related; that is, how does branching pattern influence function? This question is of more than theoretical interest. It is the entire catchment, the whole of the branched structure, that contributes water and materials to downstream reservoirs or estuaries. Water quality in recipient systems is an integral response of branching pattern, which determines how the integral is computed. Fortunately for stream ecology, the literature of geomorphology is replete with theory and metrics for understanding and describing variable branching patterns. A scaled up, segment-specific, RCC model for a trellis-shaped drainage might generate a quite different output (and retention) from that of a dendritic-shaped drainage of the same size. Shape matters. The typical textbook of fluvial geomorphology devotes equal space to channel-scale structure, process, and dynamics and to basin-scale structure, process, and dynamics. Stream ecology has focused almost exclusively on the former. Abundant tools exist for a fruitful, creative incursion into the realm of the latter.

Interestingly, branching patterns in river systems are fractal, i.e., self similar (Tarboton et al. 1988, Barbera and Rosso 1989, Rodriguez-Iturbe et al. 1994). There are no structural clues to scale; shape is scale independent (Fig. 3) which provides an opportunity to examine shape-independent functioning. To what extent is function preserved as size increases in fractal river systems? It is unlikely that function is preserved across scales. Smaller systems are likely to be more shaded, shallower, more transparent, and more subject to drying and spates than larger

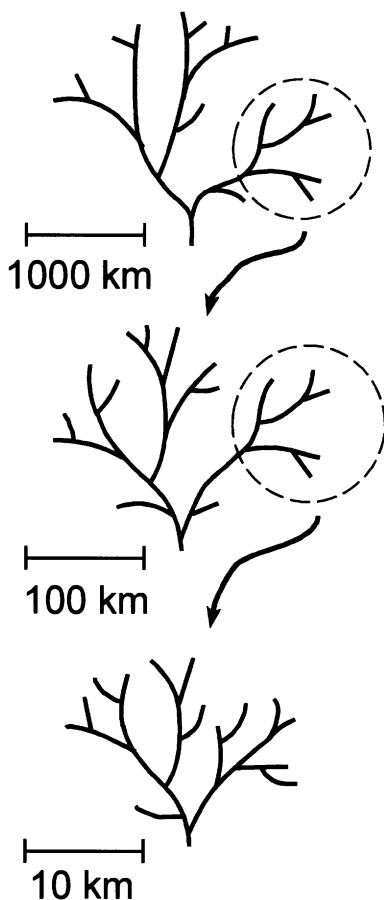


FIG. 3. The fractal nature of stream networks yields a scale-independent structure. Fragments A, B, and C have similar shapes despite their different sizes (scales). Without an accompanying scale, branching structure provides no clue to catchment size.

systems of identical shape. How these controlling factors shift in importance across scales is an intriguing question. By comparing functioning of similarly sized catchments with different branching patterns (e.g., trellis versus dendritic), we can examine dimension-independent effects of shape. This will yield a functional morphology of branched systems at the basin scale.

The science of scale is a new frontier of ecology. Its fundamental task is to determine how the configuration and dynamics of ecosystems change as scale is varied. Stream ecology can contribute substantially to this research effort by dealing with streams in their essential form—the branched structure. Multiple-scale studies of streams as unbranched lineal systems

are unrealistic and, by necessity, spatially limited.

### Beyond branching

Just as stream channels consist of more than flowing surface water, branched river systems are intimately connected to lakes, wetlands, and both shallow and deep groundwater systems. Flowing stream channels are thus the surface manifestation of a larger, integrated, planar system that represents an underlying and unifying fabric of the landscape (Fig. 2). Mean velocities, residence times, and chemical transformations vary widely in this saturated zone; however, components are inexorably linked, mixed, separated, and mixed again, always strongly spatially oriented in a downslope direction, controlled by the force of gravity, ultimately delivering transformed erosion products to the sea. Subsurface water beneath and lateral to the stream channel has been shown to be intimately connected to channel surface water and to be important in terms of both habitat and water chemistry (Stanford and Ward 1988, Triska et al. 1989, Holmes et al. 1994, Jones et al. 1995). No great leap in logic is required to extend the boundaries of the river farther up into the landscape and deeper into geologic strata. Groundwater is no less important in determining conditions for life in large river channels than are distant low-order tributaries. Some research progress has already contributed to this image of the river. Lake water chemistry and biota are sensitive to lake position in landscapes and the relative proportion of input accrued via precipitation, runoff, and groundwater (Kratz et al. 1991). Chemistry of subsurface water is shaped not only by the nature of overlying terrestrial vegetation but also by the sequential order in which water contacts different vegetation types (Giblin et al. 1991). Location and magnitude of groundwater springs can greatly affect nutrient budgets and patterns of metabolism in streams (Mulholland 1992).

The spatial image of this new concept of the river is planar. The river exists wherever water flows over or under the landscape. Rivers then are best viewed not as interdigitating with the land, but thoroughly perfusing it. Resolution of this view would require a closer partnership between watershed (catchment) ecologists who have had a largely terrestrial focus, and aquatic

TABLE 2. Exemplary questions that might arise from a shift from a linear to a branched guiding paradigm for stream research. Each question is addressable with a series of testable, explanatory hypotheses.

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1. Are RCC patterns sensitive to number of streams in each order, i.e. bifurcation ratios?
  2. If groundwater is considered a zero-order stream, how does this change the RCC?
  3. Does nutrient retention vary as a function of branching pattern?
  4. To what descriptors of the branched structure are functional attributes likely to be most sensitive?
  5. How does branching pattern influence susceptibility to disturbance by, e.g., flash flood and drying?
  6. Are there order-specific functional attributes that are not attributable to channel size?
  7. How does function vary with scale in a fractal system?
  8. How do tributary junctions of different orders influence lateral and vertical connections among channel elements *between* tributary junctions?
  9. Do patterns of branching influence patch characteristics in linear reaches?
  10. Are there performance feedbacks on morphology? What are they and how do they work?
  11. Does spiraling length change as a function of order? By what mechanism?
  12. How does branching pattern influence the position and functional role of sand and gravel bars?
  13. What are the implications of branching patterns for "in stream" ecology?
- 

ecologists working in streams, wetlands, lakes, estuaries, and oceans. More effort might be spent on flowpaths, wherever they occur. In this manner, the essential natural behavior of the river, its function—to transport, transform, retain, and connect—can be applied to the entire landscape.

### Conclusions

This excursion—based on concepts of creativity, stimulated by juxtaposition, executed by analogy, guided by visual imagery—has led to a framework which might stimulate productive stream research, broadly overlapping with ecology. The analogy with functional morphology forced clear definitions. Inspection of images uncovered a fatal flaw. The essential breakthrough was unexpectedly provided by the joint effort of a science writer and a nature photographer. Logical extension of this construct led to the heart of the terrestrial landscape via groundwater. Incorporation of groundwater as an integral part of stream ecology may be a conceptual stretch; however, several research pioneers have already crossed this frontier (e.g., McDowell et al. 1992, Valett et al. 1996). The product is not a new theory, but a research direction—a way of looking at and thinking about streams. Certainly a host of intriguing questions can be generated by this exercise (Table 2). Whether these disparate ideas will lead to a new and exciting theory of ecology, a theory that can best be developed in running waters by virtue of their essential form and function, time will tell.

My objective was not to generate a new theory or a revolutionary insight, but to explore some of the mechanisms that might be used for doing so. All of the elements of this synthesis are familiar and all of the procedures are straightforward. New ideas are assemblies of existing elements. Connections can be discovered. Creativity can be learned, fostered, nurtured, and developed. The extent to which I reached my objective is measured not by whether others are excited about my ideas, but by whether they are excited about the prospect of generating their own.

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