Geomorphology 277 (2017) 145–153

Contents lists available at ScienceDirect

Geomorphology

journal homepage: www.elsevier.com/locate/geomorph

Excursions in fluvial (dis)continuity

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ARTICLE INFO

Article history:
Received 16 February 2016
Received in revised form 19 August 2016
Accepted 29 August 2016
Available online 3 September 2016

Keywords:
Fluvial processes
Continuity
Conceptual models
Connectivity

ABSTRACT

Lurking below the twin concepts of connectivity and disconnectivity are their first, and in some ways, richer cousins: continuity and discontinuity. In this paper we explore how continuity and discontinuity represent fundamental and complementary perspectives in fluvial geomorphology, and how these perspectives inform and underlie our conceptions of connectivity in landscapes and rivers. We examine the historical roots of continuum and discontinuum thinking, and how much of our understanding of geomorphology rests on contrasting views of continuity and discontinuity. By continuum thinking we refer to a conception of geomorphic processes as well as geomorphic features that are expressed along continuous gradients without abrupt changes, transitions, or thresholds. Balance of forces, graded streams, and hydraulic geometry are all examples of this perspective. The continuum view has played a prominent role in diverse disciplinary fields, including ecology, paleontology, and evolutionary biology, in large part because it allows us to treat complex phenomena as orderly progressions and invoke or assume equilibrium processes that introduce order and prediction into our sciences.

In contrast the discontinuous view is a distinct though complementary conceptual framework that incorporates non-uniform, non-progressive, and non-equilibrium thinking into understanding geomorphic processes and landscapes. We distinguish and discuss examples of three different ways in which discontinuous thinking can be expressed: 1) discontinuous spatial arrangements or singular events; 2) specific process domains generally associated with thresholds, either intrinsic or extrinsic; and 3) physical dynamics or changes in state, again often threshold-linked. In moving beyond the continuous perspective, a fertile set of ideas comes into focus: thresholds, non-equilibrium states, heterogeneity, catastrophe. The range of phenomena that is thereby opened up to scientific exploration similarly expands: punctuated episodes of cutting and filling, discretization of landscapes into hierarchies of structure and control, the work of extreme events. Orderly and progressive evolution towards a steady or ideal state is replaced by chaotic episodes of disturbance and recovery. Recent developments in the field of geomorphology suggest that we may be on the cusp of a new paradigm that recognizes that both continuous and discontinuous processes and mechanisms play a role in fluvial processes and landscape evolution with neither holding sway over the other and both needed to see rivers as they are.

Published by Elsevier B.V.

1. Introduction

Connectivity is often seen as a virtue in fluvial systems. Whether it refers to the uninterrupted longitudinal connection between the upstream and downstream reaches of a river that supports the movement of sediment, wood, nutrients, and other mobile constituents carried by the flow; the down- or upstream migration of fish; the lateral connection between the active channel and its floodplains and other adjacent surfaces that promotes overbank flows and sediment deposition; or the connection between surface and subsurface pathways in the hyporheic zone that sustains mixing of waters of different chemistries and temperatures, connectivity is generally recognized as a desirable attribute of rivers. The goal of many river restoration activities, including dam removal; raising the bed elevation of incised channels; or removing erosion control structures, culverts, and bank protection schemes is often explicitly to “restore connectivity.” On the other hand, there is a growing recognition of the importance of disconnectivity in fluvial systems as well. Natural and artificial dams, for example, capture sediment and carbon, promote raised water tables, introduce fluvial complexity (another commonly cited virtue), forestall channel incision and evolution, and may change the fluvial and thermal regimes of rivers. Addressing both connectivity and disconnectivity, with their virtues and roles, facilitates human understanding and management of fluvial systems.

But lurking behind these concepts are their conceptual first cousins: continuity and discontinuity, a perhaps less value-laden but richer set of geomorphic ideas. Some general definitions are in order, followed by a more precise geomorphic one. According to Merriam-Webster connectivity

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http://dx.doi.org/10.1016/j.geomorph.2016.08.033
0169-555X/Published by Elsevier B.V.

refers to "the quality, state, or capability of being connective or connected," and we define disconnectivity as its antonym. From the same source, continuity refers to "the quality of something that does not stop or change as time passes;" discontinuity is its antonym. Although these definitions imply that connectivity is a spatial quality and continuity a temporal one, a more nuanced view is that continuity and discontinuity refer to processes while connectivity and disconnectivity refer to states.

In this paper we focus on fluvial geomorphology and explore how continuity and discontinuity represent fundamental and complementary perspectives on geomorphic processes, and how these perspectives inform and underlie our conceptions of connectivity in landscapes and rivers. Beginning with continuum thinking, we examine the historical roots of these concepts and how much of our understanding of geomorphology rests on contrasting views of continuity and discontinuity. In particular we argue that the continuum view has generally held sway in geomorphology because of the difficulty in predicting or modeling discontinuities, yet both are necessary to capture the full range of critical geomorphic phenomena. In particular, investigations of discontinuities have led to breakthroughs in understanding real landscapes. Finally, we show how both perspectives are needed to understand geomorphic processes and evaluate connectivity at the landscape scale.

2. Continuum thinking in fluvial geomorphology

Continuum thinking is a conception of geomorphic processes, as well as geomorphic features, that are expressed along continuous gradients without abrupt changes, transitions, or thresholds; the analogy is to a continuous mathematical function without singularities. The historical roots of this concept run deep in geological thought and underlie such seminal ideas as uniformitarianism and the balance of forces, the latter as expressed by Gilbert (1880) in discussing landscape evolution. One of the best examples of the continuum concept is Mackin's (1948) famous description of a graded river as "…one in which, over a period of years, slope is delicately adjusted to provide, with available discharge and the prevailing channel characteristics, just the velocity required for transportation of all of the load supplied from above." Mackin goes on to illustrate the correspondence between this idea and the concept of thermodynamic equilibrium as:

> A graded stream responds to a change in conditions in accordance with Le Chatelier's general law: — "if a stress is brought to bear on a system in equilibrium, a reaction occurs, displacing the equilibrium in a direction that tends to absorb the effect of the stress."

This idea of continuous readjustment of system properties so as to maintain a quasi-equilibrium state lies at the heart of many of the fundamental concepts in fluvial geomorphology. An example based on Mackin's graded stream is the Lane-Borland balance, where stream power (expressed as the discharge-slope product) on one side is balanced against sediment caliber and flux on the other, as discussed by Grant et al. (2013). What these examples have in common is the perspective that geomorphic processes reflect "delicate balances" (again in Mackin's words) of physical processes coupled by Newtonian mechanics that permit them to subtly adjust to changes in particular variables such that the systems can respond without abrupt shifts in state.

Embedded within this conception of continuity is an implicit sense of scale. Each of the examples above (balance of forces leading to landscape evolution, graded river, Lane's balance) describes the macroscopically continuous response of a system to changes in the controlling variables. Even when systems respond in this fashion, continuum behavior may not be expressed at all scales. Lane's balance, for example, posits a smooth increase of sediment flux in response to increasing stream power. At the particle scale, however, this increasing power is reflected in increasing frequency of particle entrainment, which can be viewed as a discontinuous and threshold-driven phenomenon in response to greater turbulence and increased intensity and frequency of vertical momentum fluxes in the fluid. Ultimately, as one descends through molecular and atomic length scales, all concepts of continuum Newtonian mechanics get replaced by statistical descriptions of behavior and quantum mechanics that may or may not have continuous properties. Nonetheless, continuum thinking generally rests on the aggregate scale of system behavior rather than the behavior of individual parts of the system.

Continuous geomorphic processes or formulations can be linear or non-linear. Examples of the latter include the stream power law:

$$E = KA^mS^n$$

which relates erosion rate E to upstream catchment area A, channel slope S, and bedrock erodibility K (Whipple and Tucker, 1999). Although generally non-linear due to exponents m and n typically obeying the relation $m/n \approx 0.5$, this equation functions in a continuous fashion and has been used to predict channel fluvial transport, bedrock incision, and longitudinal profile development among other applications (for review, see Dietrich et al., 2003; Lague, 2014). In fact, one of the most powerful applications of these types of continuous representations of geomorphic processes is that they can be used to predict broad patterns of underlying geological controls and anomalies, for example variations in rock uplift rate (Kirby and Whipple, 2001). It is interesting to note that more recent concepts of the stream power law now incorporate a detachment threshold, introducing a discontinuous perspective (i.e. Lague, 2014).

Continuum thinking in fluvial geomorphology is not confined to force balance or equilibrium relationships but can include spatial or temporal patterns that can be expressed in a continuous fashion. The well-known hydraulic geometry relationships are an example of a spatially defined continuum. Both the at-a-station and downstream relations are fundamentally based on the assumption of a well-behaved and continuous relationship between discharge (often represented by proxy as drainage area to some power) and quantitative descriptors of channel dimensions and dynamics, i.e., width, depth, slope, velocity, and roughness (Fig. 1). For example, the downstream power law relation between velocity (v) and discharge (Q):

$$v = kQ^m$$

is commonly derived from empirical data, often measured on multiple rivers (i.e. Leopold and Maddock, 1953), and expresses how velocity changes more or less continuously with discharge. A positive slope exponent for this relation led Leopold and Maddock to conclude that rivers actually increase their velocities with distance downstream. We will see below how a discontinuous view of the same data leads to a somewhat different conclusion.

Similarly, the development of thinking around frequency-magnitude relationships in geomorphology allowed recognition of a potentially wide range of driving events (i.e., streamflows of different frequencies and magnitudes), that when considered with a power law transport relationship (i.e., the relation between flow and transport), resulted in a relatively smooth curve of geomorphic work performed as a function of discharge (Wolman and Miller, 1960). Although an inflection in this relation is present, which the authors interpreted as reflecting a maximum of geomorphic work at roughly bankfull flow, the relationship itself did not display any singularities and could be viewed as reflecting a continuum of response to applied stress. Later studies have demonstrated that the frequency-magnitude curve is not necessarily unimodal or smooth, challenging this continuous view, but these are seen as the exception rather than the rule (e.g. Nolan et al., 1987).

Another well-studied example that incorporates continuum thinking over time is the weathering of rock to soil. The concept of a soil chronosequence inherently reflects the concept of a more or less continuous evolution of soil material through time under the influence of climate. In a review of soil chronosequence studies, Huggett (1998)

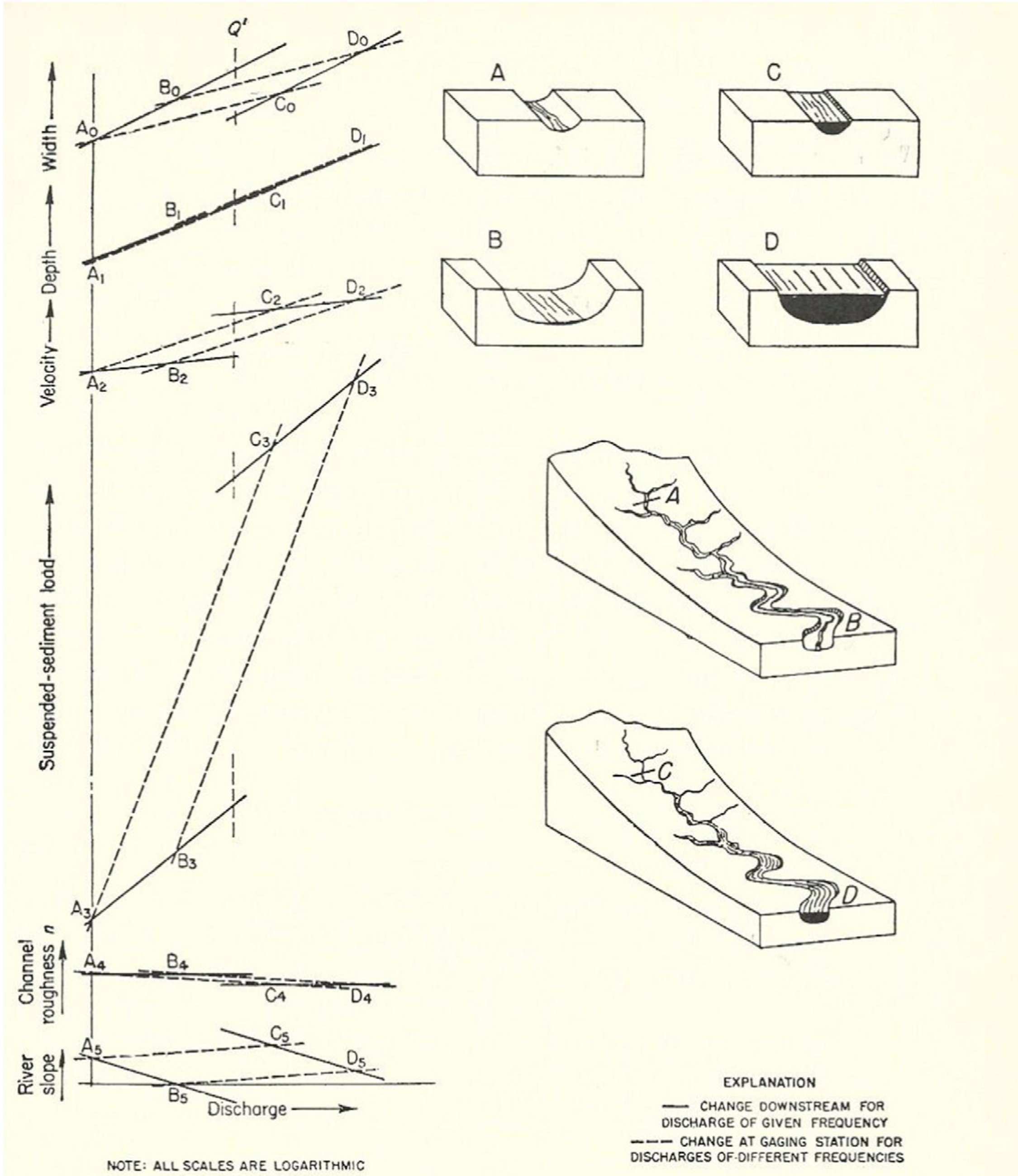

Fig. 1. Generalized hydraulic geometry relationships from Leopold et al. (1964) showing general trends for width, depth, velocity, suspended sediment, channel roughness, and slope. Note how trend lines convey continuity over the measured scales of discharge.

succinctly captures the essential contrast between a continuous and discontinuous view:

> Traditional soil formation theory sees a soil developing progressively under the influence of the environmental state factors until it is in equilibrium with prevailing environmental conditions. This developmental view of pedogenesis is supported by the classic soil chronosequence studies. A new evolutionary view of pedogenesis, which was prompted by the omnipresent inconstancy of environmental conditions and the notions of multidirectional changes and multiple steady states (as predicted by non-linear dynamics), proposes that environmental inconstancy and non-linear behavior in soil-landscapes lead to soil evolution, rather than to soil development. Soils 'evolve' through continual creation and destruction at all scales, and may progress, stay the same, or retrogress, depending on the environmental circumstances.

In considering long-term processes of soil formation or landscape evolution, the continuum view provides an easily understood framework for describing how systems change over time. Embedded within this view are assumptions that are often unstated. As Huggett (1998) points out for soil chronosequences:

> A central assumption is that the soils in the identified sequence represent successive stages of one or several pedogenic processes. Furthermore, it is assumed that the soils pass through stages characterized by some preceding member of the successional sequence.

These underlying concepts are difficult to test, although some chronosequence studies have combined well-expressed and age-constrained geological sequences with laboratory analyses to build convincing evolutionary narratives, e.g., progressive loss of silica over 4 million years through weathering of Hawaiian basalts (Ziegler et al., 2005).

The larger point is that a continuum view represents a powerful way of characterizing an evolutionary sequence but may leave out some salient elements, particularly if the sequence is punctuated by discrete events. As an example of this drawn from landscape evolution, Jefferson et al. (2010) describe channel-network and drainage-density evolution in the volcanic Cascade Range over timescales of 10^5 to 10^6 years (continuum view), but emphasize that discontinuous events (i.e., glaciation, volcanic episodes) may be necessary to “jumpstart” channel initiation and incision. At the core of the continuum view is a perspective that these discontinuous excursions do not outweigh the overall averaging provided by the continuous lens through which process-response is viewed.

2.1. Continuum perspectives beyond geomorphology

Continuum thinking is not restricted to geomorphology but provides a strong intellectual foundation for other fields including paleontology, evolutionary biology and ecology. Classic Darwinian evolution is fundamentally a continuum view of gradual change leading to speciation. As summarized by Eldredge and Gould (1972):

> Paleontology's view of speciation has been dominated by the picture of “phyletic gradualism”. It holds that new species arise from the slow and steady transformation of entire populations. Under its influence, we seek unbroken fossil series linking two forms by insensible gradation as the only complete mirror of Darwinian processes; we ascribe all breaks to imperfections in the record.

A similar perspective underlies the Clementsian view of succession as succinctly summarized by Odum (1969):

> Ecological succession may be defined in terms of the following three parameters: 1) it is an orderly process of community development that is reasonably directional and, therefore, predictable; 2) it results from modification of the physical environment by the community; that is, succession is community controlled even though the physical environment determines the pattern, the rate of change, and often sets limits as to how far development can go; and 3) it culminates in a stabilized ecosystem in which maximum biomass (or high information content) and symbiotic function between organisms are maintained per unit of available energy flow.

We are not the first to point out the correspondence in conceptual world views spanning geomorphology and ecology. More than 40 years ago, Drury and Nisbet (1971) explored the parallels in early 20th century concepts of landscape development as proposed by Davis and succession in both the plant and animal worlds as developed by Clemens and others. In all of these fields, posited continua of change were hailed as conceptual breakthroughs, and created a foundation for understanding and teaching that is well documented in the textbooks of the time. As Drury and Nisbet (1971) point out, only later do the discontinuous devils in the details begin to emerge, fraying and in some cases shredding the neat tapestries of continuum models.

Closer to our fluvial home is the River Continuum Concept (RCC) — essentially an extension of the hydraulic geometry perspective to characterize the organization of rivers in terms of the functional groups of organisms that inhabit rivers of different characteristics (Vannote et al., 1980). One can readily see how continuum thinking, as drawn from geomorphology, informs this perspective, which has been a dominant framework for stream ecologists:

> In natural stream systems, biological communities can be characterized as forming a temporal continuum of synchronized species replacements. This continuous replacement functions to distribute the utilization of energy inputs over time. Thus, the biological system moves towards a balance between a tendency for efficient use of energy inputs through resource partitioning (food, substrate, etc.) and an opposing tendency for a uniform rate of energy processing throughout the year.

Later ecological work has challenged this continuum view, pointing out the large habitat heterogeneity that exists across scales and results in some localized environments (i.e., tributary junctions) having a much richer concentration of ecological processes and life forms (e.g. Benda et al., 2004; Kiffney et al., 2006; Rice et al., 2006). But the RCC has played a major role in shaping aquatic ecological thinking for many decades.

All of these examples share several key concepts that underlie the continuum perspective. First, there is some idea of evolution or change along an orderly spectrum, with words like “gradual”, “directional”, “progressive”, or “sequential”. Second, the sequence of change itself is viewed as predictable, or at least describable, i.e., the system is reasonably well-behaved. Third, interruptions to this sequence are acknowledged but viewed as second-order effects; the underlying mechanisms of change are seen as smooth and unidirectional. Fourth, there is a suggestion that processes expressing each continuum are in quasi-equilibrium with the physical environment in which they are embedded.

These are all powerful concepts that help explain why the continuum view has played such a prominent role in diverse disciplinary fields. In particular, the ability to treat complex phenomena as orderly progressions and to invoke or assume equilibrium introduces order and prediction into our sciences. In essence, continuum views and descriptions facilitate broad understanding of landscapes. Additionally, continuous systems are easier to model, and we often redefine fundamentally discontinuous systems to appear continuous in order to make related models better behaved. In fact, there is a long-standing tradition in some fields of assuming a continuum view even though we are certain that nature itself is operating in a more discontinuous fashion. Perhaps the most common fluvial example comes from hydraulics where we typically assume that flow conditions are “steady” or at most “gradually-varying” as a means of simplifying calculations and making predictions. As Henderson (1966 pg. 2) put it:

> It is one of the most interesting features of fluvial mechanics that one may greatly simplify the analysis of a problem by changing one's point of view from, say, that of a stationary to that of a moving observer, and so changing the flow situation from an unsteady to steady one.

But there are many geomorphic and related phenomena that require a different point of view, and strict adherence to a continuum perspective comes at a cost of underappreciating and ignoring the fundamentally discontinuous nature of fluvial systems.

3. The discontinuous perspective in fluvial geomorphology

It is probably clear by now that the discontinuous view is a distinct though complementary conceptual framework that incorporates non-uniform, non-progressive, and non-equilibrium thinking into understanding geomorphic processes and landscapes. Heuristically, we distinguish three different ways in which discontinuous thinking can be expressed (Table 1). First, it can be represented in terms of discontinuous spatial arrangements or singular events. Geological contacts, waterfalls and knickpoints, dams (both natural and artificial), and discontinuous gullies are all examples of this type of physical discontinuity. Second, discontinuities can be associated with specific process domains generally associated with thresholds, either intrinsic or extrinsic, spatial or temporal. Examples of this include processes such as channel initiation or meander cutoff, and landforms such as bedrock/alluvial

Table 1
Examples of different types of discontinuities relevant to fluvial geomorphology.

Discontinuities associated with:
Spatial arrangement or singular events
Geologic contacts or structures
Tributary junctions
Dams (natural and constructed)
Extrafluvial perturbations, (i.e., landslides and lava flows into channels)
Knickpoints
Channel units (e.g., pools, rapids)
Bedforms
Discontinuous gullies and ephemeral channels
Processes or process domains (*commonly linked to thresholds, either intrinsic or extrinsic*)
Alluvial/bedrock channel
Threshold hillslopes
Thresholds of bedrock erosion
Thresholds of channel incision
Rapid changes of channel pattern (i.e., cutoffs/avulsions)
Hortonian overland flow
Bed-material entrainment
Mass movement initiation
Channel initiation
Physical dynamics (*changes in state*)
Subcritical/supercritical flow
Laminar/turbulent
Contractional vs dilational
Cavitation
Oxidization and mineral precipitation
Phase change

transitions, or cut and fill terraces. Finally, discontinuities can be expressed in terms of physical dynamics or changes in state, again often threshold-linked. Examples include subcritical versus supercritical flow, cavitation, or oxidation and/or precipitation reactions that involve rapid transformations of mineral or organic compounds. In each case, a sharp and abrupt change in system behavior accompanies a small change in applied stress or forcing. There are many other examples of each of these types of discontinuities; here we consider some examples from each class (Table 1).

3.1. Spatial and singular event discontinuities

Historically, although formal and general recognition of the importance of discontinuities in geomorphology only began to be clearly expressed in the 1970s, early geomorphologists did recognize spatial discontinuities. Perhaps the most obvious example was the stratigraphic record itself. First illustrated by Hutton's Unconformity, the record is full of breaks, discontinuities, and unconformities, leading Ager (1973) to describe the stratigraphic record as "…a lot of holes tied together with sediment."

Another early-recognized discontinuity was waterfalls. While staring at Niagara Falls, Lyell realized they were knickpoints that had to be explained by something out of the ordinary acting on the stream (Tinkler, 1987). Gilbert (1880) recognized that differences (discontinuities) in the hardness of rocks along channel beds led to differences in declivities (slope). Davis (1884) prosaically attributed most of the waterfalls in the northern U.S. states to displacement of channels by glacial ice and drift:

> At the end of the Glacial period, while the streams well south of the ice limits were still persevering in their perfect ways, those on the glaciated area often found that much of their previous work was lost and had to be done over again. As fast as the ice melted back, the rivers took possession of the country, and while the larger and stronger ones in nearly all cases found escape along their accustomed channels, many of the smaller streams were quite bewildered, and lost their way among the heaps and sheets of drift that masked their old valleys, and had to settle down as best they might on the lowest ground they could find. They were restrained in lakes and ponds behind drift barriers, and were turned aside from a life of comparative ease in their well prepared old channels to an age of hard work in active rock cutting — and here we now see them, just accommodated to their new lines of life.

Discontinuities in a form of this sort that indicated disruptions of the "ideal" geographical cycle were a major problem for Davis. He termed them "accidents" or "interruptions" and repeatedly claimed that the cycle of erosion was a sufficiently elastic theory to admit such inconveniences (see discussion in Chorley et al., 1973).

Dams, whether natural or man-made, are another widely recognized discontinuity in rivers and there is a deep and rich literature describing their short and long-term geomorphic effects (for a review, see Grant, 2012). Although widely seen as blockages that interrupt the flow of water, sediment, and other river constituents, dams (at least natural ones) can also accelerate erosional processes if and when they breach catastrophically. Such singularities and historical events can have an overriding influence on channel characteristics (O'Connor et al., 2003), above and beyond that predicted by continuous analysis frameworks such as the stream power law.

A sharp contrast can be drawn between the continuous and discontinuous perspectives on how rivers change their dimensions as a function of discharge or distance downstream. This distinction served as the basis of a famous controversy between Leopold and Mackin over how to interpret hydraulic geometry relations, and, more broadly, how to do science. Leopold and Maddock (1953) had shown that hydraulic geometry relations varied more or less continuously in relation to discharge. Mackin replotted the data on downstream variations in velocity for individual rivers (as opposed to amalgamating many rivers together) and showed that Leopold and Maddock's conclusion that velocity increased downstream was not a global effect but rather varied river to river as a consequence of particular river geometries and circumstances (Fig. 2) (Mackin, 1963). Mackin's replotting revealed the fallacy that rivers change continuously downstream. Instead, rivers vary discontinuously downstream in flow and dimensions as tributaries join, rocks of different hardness are crossed, and sediment of different caliber is introduced. These contrary analyses reveal how the same data can yield different models depending on whether a continuous or discontinuous world view is employed.

One of the clearest recent expressions of discontinuous thinking in geomorphology is the interest in channel classification across a range of scales (for review, see Kondolf et al., 2003). Whereas river channels were previously seen as continua that could be described by hydraulic geometry relations, they are now perceived as consisting of distinct; definable; and typically hierarchically organized units, reaches, segments and so forth. These fundamental discretizations of channels are, in turn, seen as providing key descriptors for both geomorphic and ecological organization (Frissell et al., 1986; Grant et al., 1990; Montgomery and Buffington, 1988, 1997).

Discontinuities can also be perceived in singular events. Historically, emphasizing the geomorphic importance of extreme and outsized events seemed to challenge the existing continuum paradigm, as reflected in the querulous title adopted by Dury (1975) for his early exploration of the subject: "Neocatastrophism?". Perhaps invoking exceptional events evoked too strongly discredited Noachian narratives; certainly those like J Harlan Bretz who early in the 20th century proposed megafloods as the cause of the unusual landforms in the Channeled Scablands of Washington State were not treated kindly (Baker, 1978).

3.2. Discontinuities associated with process domains and thresholds

The growing interest in discontinuous geomorphic perspectives in the latter half of the 20th century, however, is evident in the theme of the 1978 Binghamton Symposium "Thresholds in Geomorphology"

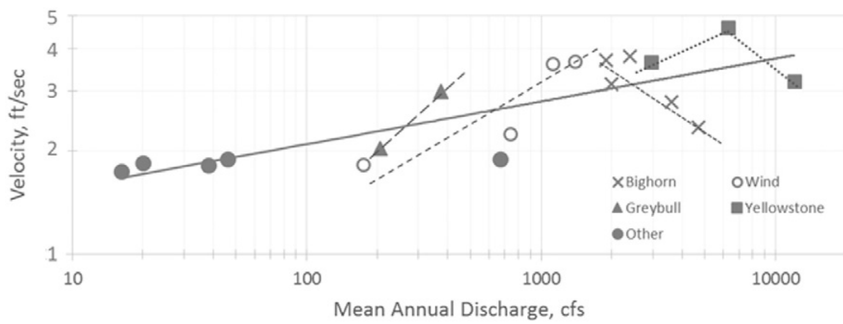

Fig. 2. Downstream hydraulic geometry relation for velocity for selected rivers, after Mackin (1963). Note non-uniform and opposite trending relations between velocity and discharge.

followed by a meeting dedicated to "Catastrophic Flooding" in 1987 (Sawyer et al., 2014). For many, the concept of thresholds served to introduce a discontinuous perspective into geomorphic thought, and Schumm's (1979) seminal paper on the subject showed how the punctuated nature of many geomorphic events and trajectories could be reconciled with Davisian concepts of uniformity and continuous change (Fig. 3). What made this view particularly exciting yet challenging was that it posited that landscapes were inherently complex, with both continuous and discontinuous trajectories occurring over different timescales and in different portions of the landscape. That a landscape could be viewed as both continuous and discontinuous simultaneously was a bit akin to seeing light as both particle and wave; both were true. The forerunner of this perspective was the classic paper by Schumm and Lichty (1965) a decade earlier that illustrated how the same landscape characteristic, for example channel or valley morphology, could be seen as either a dependent or an independent variable, depending on one's timescale of interest. This perspective also foreshadowed the later conception of landscapes as being simultaneously composed of equilibrium, disequilibrium, and non-equilibrium landforms (Renwick, 1992).

Although Schumm's work focused primarily on landscape evolution, in the broader sense his introduction of the concept of thresholds, both extrinsic and intrinsic, presaged many new ways of looking at geomorphic systems. For example, the conception that rivers can exist in various states – alluvial, bedrock, mixed – is founded on the idea that the critical entrainment threshold, commonly represented as a Shields number, can be used along with sediment supply rates to discriminate and even predict river bed states and bedrock erosion rates (e.g. Sklar and Dietrich, 2004).

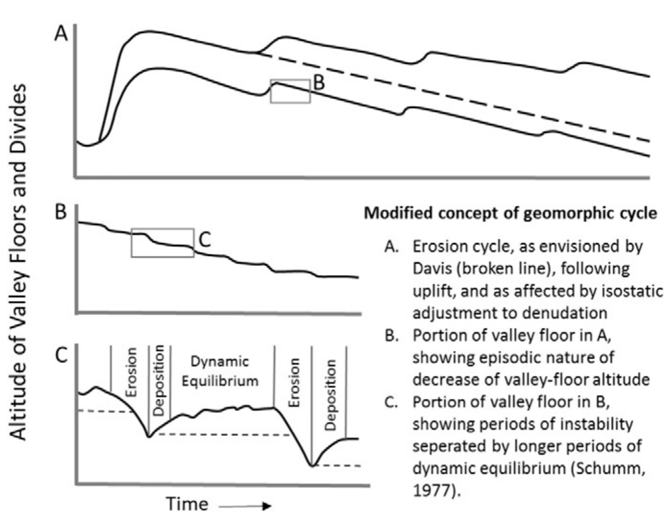

Fig. 3. Alternate models of landscape evolution showing both continuous (dynamic equilibrium) and threshold-punctuated evolutionary trajectories. After Schumm (1979).

These types of studies have given rise to what could almost be seen as a new paradigm that directly owes its origin to the discontinuity perspective: the importance of heterogeneity within rivers, particularly as a foundation of ecosystem health and biodiversity, and as a goal of stream restoration. The roots of this concept probably lie with the emergence of the "intermediate disturbance model" in a classic paper by Connell (1978), which stresses the importance of episodic but not extreme disturbances as drivers of ecosystem heterogeneity. This heterogeneity is reflected in both the structure of the ecosystem and its physical habitat. As Palmer et al. (2010) noted:

> A dominant paradigm in ecological restoration is that increasing habitat heterogeneity (HH) promotes restoration of biodiversity. This paradigm is reflected in stream restoration projects through the common practice of re-configuring channels to add meanders and adding physical structures such as boulders and artificial riffles to restore biodiversity by enhancing structural heterogeneity.

Palmer and others go on to argue that while river restoration has been effective in re-introducing physical heterogeneity into rivers, there has not been a corresponding increase in biodiversity. The larger point here, though, is that recognizing the heterogeneity of rivers has become a fundamental linchpin of strategies for river restoration; whether it works or not remains to be seen.

3.3. Discontinuities associated with physical dynamics and changes in state

This third class of discontinuities represent process realms where abrupt changes in system behavior occur, either involving thresholds or not. Well-known examples from fluvial hydraulics include the transition from sub- to supercritical flow (which involves a threshold at critical flow) or the transition from laminar to turbulent flow, where the threshold is more diffuse. Other threshold-driven discontinuities involve phase changes from solid to liquid to gas or the onset of cavitation. Discontinuities can develop where chemical or physical gradients are strong, for example along weathering fronts or fractures. The key characteristic of these discontinuities is that they reflect the fundamental physics underlying system behaviors and are therefore, in a sense, non-negotiable. While other classes of discontinuities may depend on one's point of view or scale of inquiry, these types of discontinuities do not and are therefore embedded in the very fabric of how rivers behave and respond to perturbations.

The fluvial responses to changes in process realm are non-trivial. Fluctuations between sub- and supercritical flow, for example, are a major source of flow resistance in steep channels, and the channels and their bedforms are organized to maintain near-critical flow (Grant, 1997). Phase change transitions dictate whether rivers transport ice or water with all the concomitant effects on channel morphology and sediment transport (Etterna, 2002). Cavitation has been implicated in fluvial erosion of bedrock (O'Connor, 1993; Whipple et al., 2000). Precipitation of aluminum and other oxides from an active weathering front can change the chemistry of stream waters (i.e. Bove et al.,

2007) and may result in ferricrete formation that dictates channel morphology (Nanson, 2005). All of these processes rest on physics-based discontinuities.

3.4. Parallel concepts of discontinuity in other fields

There has been a remarkable development of the discontinuity perspective in other fields that closely parallels that in geomorphology. Starting in the late 1970s, punctuated equilibrium replaced gradualism as a fundamental rubric in paleontology and evolutionary biology (Stanley, 1981). Disturbance ecology and patch dynamics emerged as fundamental themes in terrestrial ecology, sweeping aside continuum models of succession and providing the foundation for the new field of landscape ecology (Forman, 1995; Pickett and White, 1985). Similar developments occurred in aquatic and riverine ecology (Benda et al., 2004; Kiffney et al., 2006; Rice et al., 2006; Ward, 1998). As a consequence, improving heterogeneity and diversity became goals for both terrestrial and riverine restoration and conservation.

Several key points emerge from this discussion of discontinuity. First, in moving beyond the continuous perspective, a fertile set of ideas come into focus: thresholds, non-equilibrium states, heterogeneity, and catastrophe. The range of phenomena that are thereby opened up to scientific exploration similarly expands: punctuated episodes of cutting and filling, discretization of landscapes into hierarchies of structure and control, the work of extreme events. Orderly and progressive evolution towards a steady or ideal state is replaced by chaotic episodes of disturbance and recovery. This expansion of viewpoints has led to many rich research directions. Finally prediction becomes more challenging but not impossible; linear models of system change must now incorporate singularities, cusps, and strange attractors (c.f. Wilcock and Iverson, 2003). But these models thereby become more interesting and relevant to a complex world.

4. The emerging paradigm of (dis)continuity?

Is this a new paradigm that recognizes that both continuous and discontinuous processes and mechanisms play a role in fluvial processes and landscape evolution, or just old wine in a new bottle? What new insights would be afforded by this expanded view? One might well argue that the field of geomorphology has already seen numerous efforts to characterize landform and landscape development in terms similar to what we describe here. In particular, ever since Chorley's seminal book on the subject there has been a long history of applying theoretical concepts from general systems theory and thermodynamics to the study of landforms, resulting in diverse and sometimes dichotomous perspectives on how landscapes evolve as, for example, open/closed systems (Chorley, 1962), energetically most probable versus random states (Leopold and Langbein, 1962), equilibrium versus non- or disequilibrium (Renwick, 1992) and chaotic versus deterministic (Malanson et al., 1992; Phillips, 2006) among others.

These perspectives have enriched the field of geomorphology by highlighting the complexity of geomorphic responses to perturbations that cannot be simply predicted by force balance considerations or reference to historical antecedents. Instead, multiple evolutionary pathways exist for landforms, and both general principles and local contingencies determine which path the landscape follows (Phillips, 2006). Within this context, discontinuities represent bifurcations in these paths; from Phillips (1992):

> Nonlinear dynamical systems often exhibit discontinuities in their evolution, called bifurcations. These discontinuities may represent a transition from one equilibrium state to another, or from regular or periodic behavior to chaos. Analytically, these discontinuities can be explored and described using bifurcation and stability analysis and catastrophe theory. Bifurcations in nonlinear dynamical systems are directly analogous to thresholds in geomorphic systems.

In introducing a typology of continuous and discontinuous perspectives in geomorphology our goal is not to add yet another dichotomy to the field nor to recast this prior theoretical work, but to offer a potentially more approachable construct both for understanding the history of geomorphic thought and recognizing (and reconciling) the fundamental duality of geomorphic phenomena in a readily observable fashion.

We see signs of an expanding capacity to use (dis)continuity when interpreting watershed processes. As this discussion has revealed, these are complementary, not competing, perspectives, and both add insight. The utility of (dis)continuity as a concept is that it can be used to characterize processes and patterns without having to determine or assess notoriously difficult to measure aspects of system behavior, such as where landforms or landscapes sit with respect to equilibrium or thresholds. Instead, acknowledging the role of (dis)continuous processes and behaviors is akin to understanding light as both particle and wave.

As an example of what this joined perspective might look like, consider recent work on the development of river networks in volcanic landscapes in the Oregon Cascade Mountains (Jefferson, 2006; Jefferson et al., 2010) (Fig. 4). The question at the core of this work is how does a young landscape constructed of thick, highly permeable lava flows evolve to the point that surface flow and channels can persist and incise the topography? Jefferson et al. (2010) posit a role for both continuous processes such as soil formation on young lava flows, weathering, and clay formation that seal the surface, and discontinuous processes such as volcanism and glaciation that both introduce fine material that further reduces permeability; glaciation also jumpstarts incision of channels. Continuous and discontinuous processes play out simultaneously but their effects are felt at different timescales (Fig. 4). Development of drainage density requires both processes, with neither holding sway over the other.

Although this is only an example, it points towards how we might see and model river dynamics and landscape development in the future. For models to accurately capture landscape behavior, they have to incorporate discontinuous processes and mechanisms: rapid tectonic events, catastrophic floods, wildfires, volcanic eruptions, landslides and dams. But they also have to represent the slow, progressive, inexorable workings of continuous processes. And the scaling relationships between the continuous and discontinuous must be represented accurately. This latter step is key and will require considering the effectiveness of different processes of different frequencies and magnitudes, an idea first expressed by Wolman and Gerson (1978). Their vision of a geomorphology that recognizes both formative events and the intervals between those events as equally important seems prescient in light of our current understanding. But this idea is also reflected in more recent work that seeks to reconcile variable sediment yields over decadal, centurial, and millennial timescales (e.g., Kirchner et al., 2001).

5. (Dis)continuity and (dis)connectivity

We come full circle by considering the relation between the concepts we've been discussing and the theme of this year's Binghamton Symposium: Connectivity in Geomorphology. While there is not a perfect mapping between (dis)continuity and (dis)connectivity, the first fundamentally informs the second. As noted previously, connectivity is best seen as a state, and landscape connectivity can be viewed as a state where continuity of process and form is preserved. Both meanings are present when disconnectivity or discontinuity are seen primarily as the result of barriers or blockages due to biogenic, extrafluvial (sensu Ely et al., 2012) or artificial dams (Burchsted et al., 2014). An undammed river is the classic example of a connected river, where water, sediment, fish, wood, and other watershed constituents move freely downstream under the pull of gravity, or swim upstream in the case of fish. Yet discontinuity applies here too: sediment starts and stops, bedrock gives way to alluvium which gives way to bedrock, the discharge grows as a step function by tributary addition, patches of

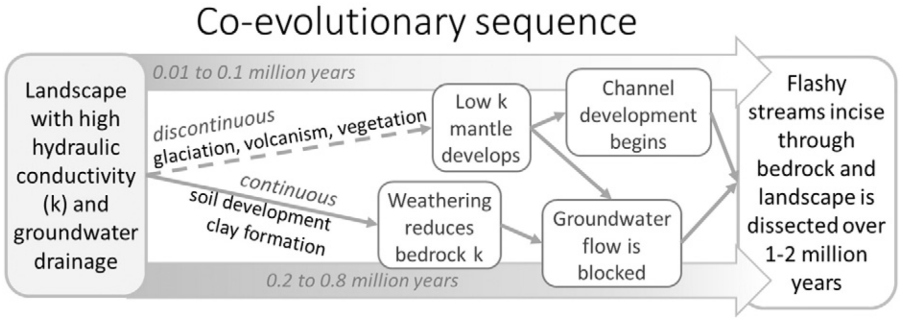

Fig. 4. Proposed trajectory for development of drainage density in the Oregon Cascades, after Jefferson (2006). Note that both continuous and discontinuous processes are actors in this scenario. While the continuous processes may take hundreds or thousands of years to play out, discontinuous processes acting over a much shorter timescales can jump start or accelerate the evolutionary sequence.

vegetation with diverse ages record the last floods, rapids come and go. The connected river displays (dis)continuity at many scales; the disconnected or dammed river does the same (Wohl and Beckman, 2014).

These rather awkward words – (dis)connectivity and (dis)continuity – reveal a striking truth: that we have no words in English for this phenomenon of both being continuous (connected) and discontinuous (disconnected) at the same time. Perhaps if we did, these concepts would seem more natural and less oppositional to us. Beyond seeing these concepts as virtues or vices is to recognize that they are fundamental properties of rivers that need to be acknowledged and given their due in the way we conceive of the fluvial system and its evolution. This involves accepting rivers as they are, not as we wish them to be.

Acknowledgements

The authors wish to thank Sarah Lewis for her considerable help in editing and refining the manuscript. We also thank excellent reviews by Frank Magilligan, Jon Major, and an anonymous reviewer. Any use of trade, firm, or product names is for descriptive purposes only and does not imply endorsement by the U.S. Government.

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