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The stream evolution triangle: Integrating geology, hydrology, and biology

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Abstract

The foundations of river restoration science rest comfortably in the fields of geology, hydrology, and engineering, and yet, the impetus for many, if not most, stream restoration projects is biological recovery. Although Lane's stream balance equation from the mid-1950s captured the dynamic equilibrium between the amount of stream flow, the slope of the channel, and the amount and calibre of sediment, it completely ignored biology. Similarly, most of the stream classification systems used in river restoration design today do not explicitly include biology as a primary driver of stream form and process. To address this omission, we cast biology as an equal partner with geology and hydrology, forming a triumvirate that governs stream morphology and evolution. To represent this, we have created the stream evolution triangle, a conceptual model that explicitly accounts for the influences of geology, hydrology, and biology. Recognition of biology as a driver leads to improved understanding of reach-scale morphology and the dynamic response mechanisms responsible for stream evolution and adjustment following natural or anthropogenic disturbance, including stream restoration. Our aim in creating the stream evolution triangle is not to exclude or supersede existing stream classifications and evolutionary models but to provide a broader "thinking space" within which they can be framed and reconsidered, thus facilitating thought outside of the alluvial box.

KEYWORDS

channel evolution model (CEM), conceptual model, fluvial geomorphology, river restoration, stream evolution model (SEM), stream classification

1 | INTRODUCTION

The stream evolution triangle (SET) is a conceptual model that blends long-established principles of fluvial geomorphology with results emerging from recent research revealing the high degree to which biological agents affect stream processes and systems (Atkinson, Allen, Davis, & Nickerson, 2018; McCluney et al., 2014). Conceptual models are useful when attempting to integrate information from natural science disciplines in order to understand complex systems (Fortuin, van Koppen, & Leemans, 2011) and are consequently well-suited to fluvial systems. With the SET, we attempt to create a conceptual space inclusive enough to represent wide ranges of process drivers, stream forms, and evolutionary pathways but simple enough to allow for creative thinking and rapid evaluation of both established and new ideas (Jackson, Trebitz, & Cottingham, 2000).

In common with existing stream classifications (e.g., Leopold & Wolman, 1957; Montgomery & Buffington, 1993; Rosgen, 1996; Schumm, 1985 [Figure 1]) and evolution models (e.g., Cluer & Thorne,

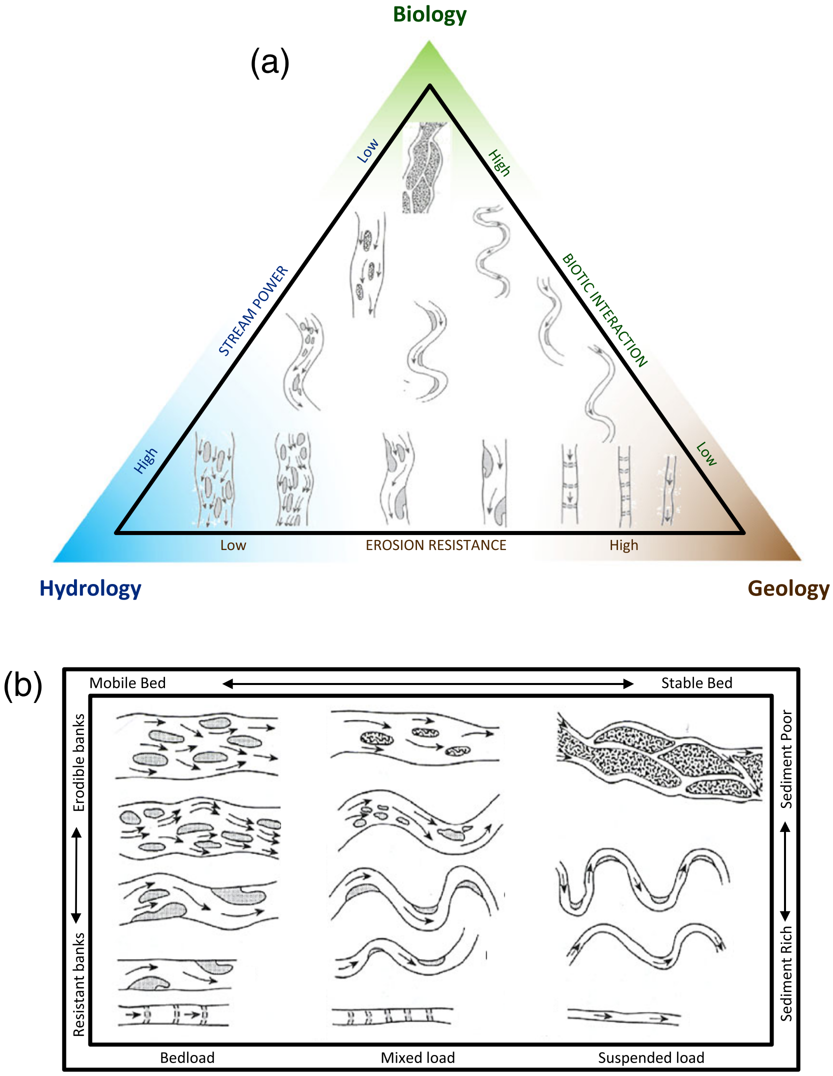

FIGURE 1 (a) Stream evolution triangle with the planform patterns defined by Schumm (1985) used to illustrate typical morphologies that might be expected in different process domains within the triangle. The stream evolution triangle represents the relative influences of geology (erosion resistance), hydrology (stream power), and biology (biotic interaction); (b) channel patterns after Schumm (1985), adapted from Knighton (1998) [Colour figure can be viewed at wileyonlinelibrary.com]

2014; Schumm, Harvey, & Watson, 1984; Simon & Hupp, 1986), the SET provides an inclusive framework for qualitative interpretation, evaluation, and forecasting of current and potential future stream forms or "stages," taking into consideration the effects of historical path dependency, current evolutionary trajectory, and dynamic responses to natural or anthropogenic disturbance. To do this, the SET represents the relative influence of three drivers of stream form and function: geology, hydrology, and biology, while recognising that these high-level drivers operate through well-known but derivative drivers, including catchment topography and rainfall–runoff relationships, valley slope and confinement, flow regime, sediment regime, channel boundary characteristics, and vegetation. The SET broadens the science base on which river forms and dynamics are considered, while incorporating the principles that underpin existing classifications and conceptual models, rather than seeking to replace them. Consequently, within the SET, it is possible to delineate "process domains," stream types, and evolutionary stages associated with many well-established stream classifications.

The novelty of the SET does not lie in its recognition and adoption of high-level drivers, which is not new (see Schumm & Lichty, 1965). Neither is it a departure from tradition to see that identification of these high-level drivers leads naturally to identification of process domains, within which particular combinations of derivative drivers dominate (Montgomery, 1999). The SET facilitates this too but does so with explicit inclusion of biology as a high-level driver, which leads to improved understanding of the reach-scale dynamic response mechanisms long recognised as being responsible for complexity in stream evolution and response to disturbance (Hey, 1979).

Although geology and hydro-climate feature as primary drivers in existing approaches to stream classification and hydraulic geometry analysis, vegetation has long been described as a secondary or derivative driver (Hickin, 1984; Montgomery, 1999), and biology, more broadly, has been underrepresented or absent. Recognising this omission, the SET expands the lens through which geomorphologists, engineers, and river scientists view the river from one that has historically focussed almost exclusively on physics-based science to one that explicitly includes biological processes (Figure 1).

The conceptual or "thinking" space within the SET is bounded by three axes rather than the two customarily used in existing stream classification and evolution diagrams. However, the principle remains that of organising stream characteristics and sequences of change into meaningful patterns, based on measures of similarity and difference (Naiman, Lonzarich, Beechie, & Ralph, 1992). With respect to process response, the balance between hydrology and geology is implicit to the basal axis of the SET, along which the influence of biology is minimal. This accords with Lane's balance (Lane, 1955), which represents alluvial channel stability solely as a function of stream power (hydrology) and sediment supply/calibre (geology).

Physics-based stream classification has advanced our understanding of river form and process, and its application has proven useful in the contexts of river engineering, management, and restoration. However, a limitation of conventional stream classifications is the perception that there is a finite number of enduring stable stream types that change only in response to an extreme event or a step change in one of the controlling variables. This can lead to an erroneous conclusion that a stream of a designated type will not, and perhaps should not, change through time.

Channel and stream evolution models (CEMs or SEMs) provide an alternative to morphological classifications in that they characterise streams in terms of patterns and trends of adjustment, rather than stasis (Cluer & Thorne, 2014; Schumm et al., 1984; Simon & Hupp, 1986). Although useful for describing and understanding temporal and spatial sequences of change, existing evolutionary models also rely on physics-based arguments and explanations, eschewing consideration of the influence of biological agents in conditioning, let alone driving morphological change. In this context, the SEM represented an advance over earlier CEMs in that it associates the range and value of ecosystem benefits provided by an incised stream with its stage of evolution. However, the SEM still frames ecosystem functions as being dependent on the morphological outcomes of fluvial processes, rather than representing biology as an evolutionary driver in its own right.

In summary, existing stream classifications and evolutionary models start with the premise that river form results from physical interactions between the flow regime, sediment regime, and channel boundary materials. In the SET, we cast biology as an equal partner with geology and hydrology, forming a triumvirate that governs stream morphology, drives morphological adjustment, and steers the sequential path along which disturbed streams evolve. Further, the SET recognises that the form, function, and evolutionary trajectory of a stream may be dominated by a single driver, a pair of drivers, or (more usually) some combination of all three, depending on its catchment, landscape, and management contexts.

2 | FOUNDATIONS

The SET depicts the relative influences of geology, hydrology, and biology on stream form and process (Figure 1). Triangular representations of three characteristics or traits are well established in natural science and are known as ternary or triangle plots or diagrams (Flemming, 2000; Frohlich, 1992). Hence, the SET can appropriately be described as a ternary diagram.

Stream types may be differentiated in the SET depending on where they plot in terms of the relative influences of geology, hydrology, and biology. Streams with one predominant driver will plot close to that corner of the triangle. Streams with codominant drivers, such as island-braided streams controlled by biology and hydrology, will plot midway along the axis connecting those drivers. Conversely, if all three drivers have equal influence, a stream plots near the centre of the triangle. It follows that in terms of stream classification, the space within this ternary diagram represents a wide range of driver-defined process domains and associated stream types and evolutionary trends. It further follows that when there is a change in the relative influences of the high-level drivers, this alters the plotting position, reflecting a shift in process domain that initiates a responsive adjustment in stream form along a new evolutionary path.

Stream responses may be relatively simple and short lived or complex and long-lasting, depending on the magnitude and duration of the causal change in one or more of the drivers. For example, a flood event temporarily increases the influence of hydrology, shifting the plotting position towards the “hydrology” corner. The relative influences of geology and/or biology must decrease, because the three relative influences must sum to 100%. After a flood, the influence of hydrology returns to its pre-event value, and the plotting position shifts away from the hydrology corner.

The potential for more complex responses to disturbance can be illustrated by the impacts of a drought. If the drought is short lived, the plotting position shifts away from the hydrology corner, increasing the relative influences of geology and/or biology. When the drought ends, the influence of hydrology returns to its pre-event value, and the plotting position shifts back towards the hydrology corner. However, if the drought is severe, it not only may reduce river flows but also may stress riverine ecosystems—thus diminishing the influence of biology as well as hydrology. When an event directly affects multiple drivers, adjustments to changes in their relative influences become more difficult to evaluate and predict. Also, stream adjustments to an event impacting more than one driver will likely be protracted, nonlinear, and morphologically complex.

3 | UNDERSTANDING THE DRIVERS AND THEIR INFLUENCES

Geology is a process driver because highly erosion-resistant boundary materials, such as intact bedrock, coarse colluvium, strongly cohesive clays, or cemented sediments, limit the capacity of a stream to adjust its geometry, at least over multidecadal timescales. But erosion resistance is just one of numerous ways that geological influences on stream form and process can be represented (Figure 2a).

The decreasing influence of geology can also be characterised using bands that grade from “source,” through “transport,” to “response” (Montgomery & Buffington, 1993; Figure 2b). In source reaches, primary erosion supplies weathered rock and colluvium to the fluvial system. These reaches are nonalluvial and insensitive to disturbance. In transport reaches, sediment loads are limited by the supply of sediment from local and upstream sources. This makes them more sensitive to disturbance than source reaches but less sensitive

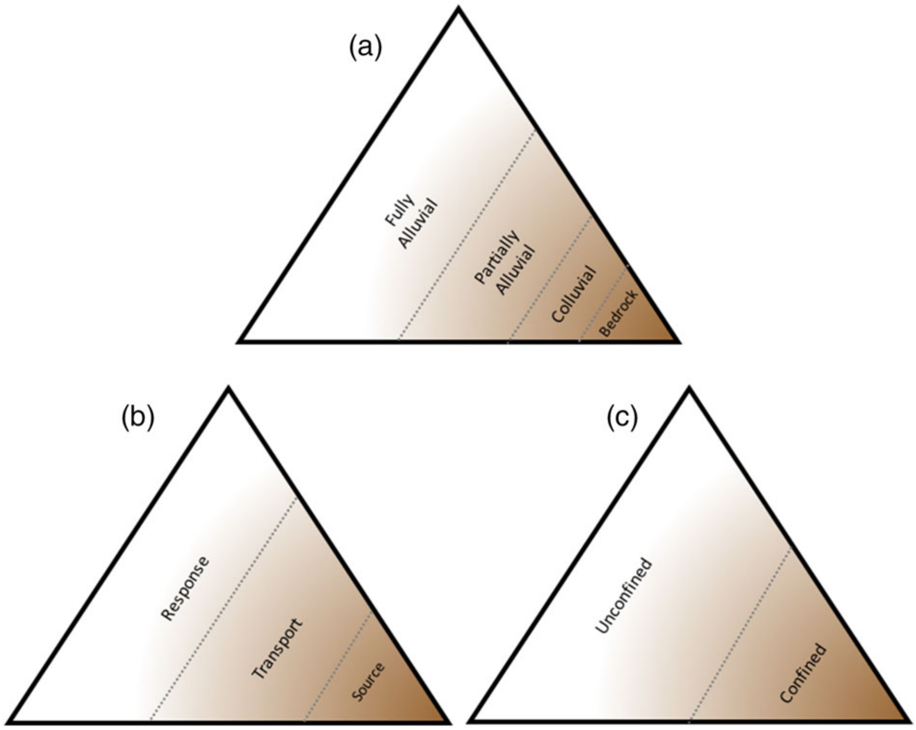

FIGURE 2 Examples of decreasing influence of geology with distance from the "geology" corner of the stream evolution triangle [Colour figure can be viewed at wileyonlinelibrary.com]

than fully alluvial response reaches, where sediment loads are limited only by the capacity of the stream to transport alluvium.

The importance of valley confinement is highlighted by Fryirs, Wheaton, and Brierley (2016). Streams vary from those that are geologically "confined" within narrow valleys to those that are "unconfined" because they flow through wide valleys with space for development of streams with meandering, braiding, or anastomosing planforms (Figure 2c). When an alluvial stream is channelised, incised, and/or stabilised by river engineering, process–response mechanisms are distorted, and morphological outcomes artificially mimic those of geological confinement. Consequently, in the SET, the impact of constructing nonerodible structures is to shift the plotting positions of naturally alluvial or partially alluvial streams towards the "geology" corner of the triangle.

Geologically controlled and artificially stabilised channels are relatively simple, typically featuring rectangular, trapezoidal, or triangular cross sections, with longitudinal slopes dictated by landscape gradients, and single-thread planforms that follow faults, lineaments, narrow valleys, or anthropogenically fixed courses. These streams are resilient to fluvially driven, morphological change even when subjected to extreme hydrological events. They are also insensitive to changes in the associated biological communities. Consequently, streams that plot close to the geology corner of the SET are relatively unresponsive to disturbance, and their morphologies are persistent—at least over steady (Schumm & Lichty, 1965) and human timescales. Even in such geologically controlled streams, heavy wood loading can result in more complex morphologies and habitats, which could move these streams towards the biology corner.

Hydrology is a process driver because it is energy imparted to the landscape by flowing water that powers fluvial processes. Channel dimensions scale on stream discharge, and thus, the relative influence of hydrology is often dominant in very large rivers, generally tending to diminish as stream size decreases. However, all aspects of the flow regime affect the influence of hydrology on stream form and function (including flow frequency, magnitude, seasonality, and duration), and particular attributes and combinations of attributes act to intensify or weaken the influence of hydrology. Hence, there are multiple ways other than the discharge magnitude to characterise how the influence of hydrology increases with proximity to the hydrology corner.

The influence of hydrology is amplified in arid areas where mean annual discharge is low but morphological effectiveness is high due to storm-dominated, flashy flows (Skidmore et al., 2011). For example, the Gila River in the Sonora Desert was observed to widen by a factor of 20 during a single flood event, with the impacts of that single storm persisting for half a century (Burkham, 1972). Hence, the Gila River would plot close to the hydrology corner in the SET despite its relatively low mean annual flow. At the other end of the flow variability, spectra are spring-fed streams with nearly flat annual hydrographs, such as the Deschutes River, Oregon, whose channel has changed little over centuries (O'Connor, Grant, Curran, & Fassnacht, 1999). Between these extremes, flow regimes range from those in basins subject to rain-on-snow flood events, through rivers characterised by low-intensity, long-duration rainfall and runoff from frontal depressions to high-alpine, snow-fed streams that rarely experience rainfall at all (Figure 3a).

The natural flow regimes of many streams and rivers have been purposefully or inadvertently altered by catchment and water

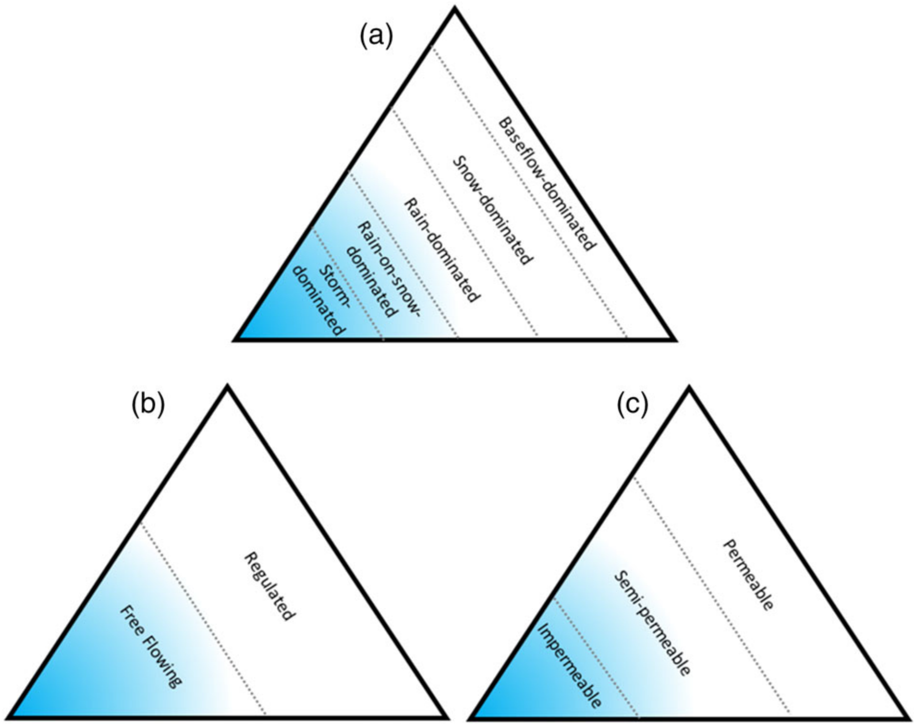

FIGURE 3 Examples of decreasing influence of hydrology with distance from the "hydrology" corner of the stream evolution triangle [Colour figure can be viewed at wileyonlinelibrary.com]

resource development, with impacts that may either truncate or magnify the influence of hydrology. For example, using dams and diversion channels to reduce natural flow, variability shifts the plotting positions of regulated rivers away from the hydrology corner (Figure 3b). Conversely, urbanisation that significantly increases the proportion of the catchment that is impermeable has been shown to increase flows and flashiness, shifting affected streams closer to the hydrology corner (Figure 3c).

Hydrologically dominated and unregulated streams are more responsive to fluvially driven, morphological change because hydrology drives channel adjustments, whereas geology and biology generally resist them. Due to their alluvial nature and lack of biological control, hydrologically dominated streams are temporally variable and complex, typically featuring braided channels with mobile beds and high width-to-depth ratios. Hydrologically dominated streams are also sensitive to changes in the associated biological communities through, for example, colonisation of bars by woody vegetation (Bertoldi et al., 2015). Consequently, streams that plot close to the hydrology corner are more responsive to disturbance than those near the geology corner, and their morphologies are transient and changeable over steady (Schumm & Lichty, 1965) and human timescales.

Biology is a process driver because energy imparted to the landscape by organisms drives biogeomorphic processes as well as modifying fluvial processes. The effectiveness of biology as a process driver has long been recognised through, for example, the statistically significant impact of dense, woody bank vegetation on the stable widths of gravel-bed rivers (Hey & Thorne, 1986). Evidence of the influence of vegetation on river form also comes from the sedimentary record, where concordance has been shown between the appearance and spread of trees in fluvial landscapes during the Devonian and Carboniferous periods (between about 300 and 420 million years ago), and planform transitions from sheet braided to meandering and then anastomosed (Davies & Gibling, 2010). Conversely, a close association between the disappearance of vegetation and planform metamorphosis was demonstrated by a switch from meandering to braiding in South African rivers when vegetation was eliminated during the Permian–Triassic extinction, about 250 million years ago (Ward, Montgomery, & Smith, 2000).

The morphological impacts of vegetation have received considerable attention and clearly demonstrate one way in which biology affects river forms and processes. In the SET, the influence of vegetation can be represented by plotting streams with riparian zones colonised by wetland obligate species near the apex because there is frequent and close interaction between vegetation and the stream. However, streams surrounded by upland vegetation species plot closer to the base because such vegetation rarely, if ever, interacts directly with stream flows (Figure 4a).

Upland species may still, indirectly, affect stream processes having been recruited by the stream through lateral erosion and/or gravity-induced, mass failure. This is the case because although live vegetation (including standing trees) significantly influences stream forms and functions, a considerable body of research establishes that trees continue to impact fluvial processes even after their demise, in the form of large wood pieces and log jams (Abbe & Montgomery, 1996). Indeed, reintroduction of large wood and construction of engineered log jams have become staple actions in modern river

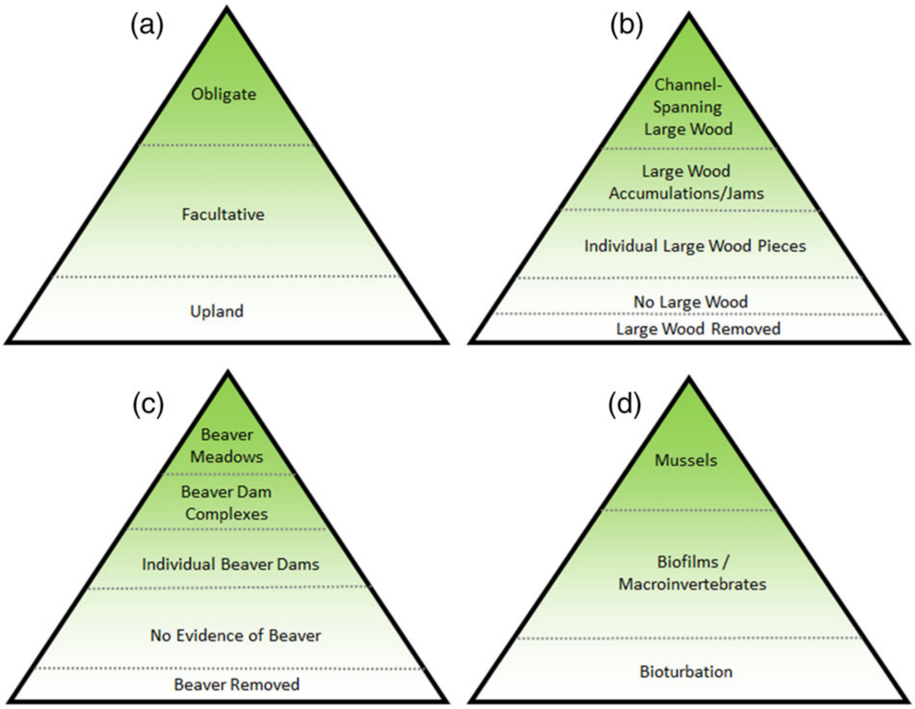

FIGURE 4 Example of decreasing influence of biology with distance from the "biology" corner of the stream evolution triangle expressed through (a) riparian vegetation by wetland indicator status rating (Lichvar, Melvin, Butterwick, & Kirchner, 2012; obligate = almost always occurs in wetlands; facultative = occurs in wetlands and nonwetlands; upland = almost never occurs in wetlands), (b) presence and abundance of large wood, (c) presence and relative dam building activity of beaver; and (d) biologically induced bed stability or instability [Colour figure can be viewed at wileyonlinelibrary.com]

restoration. This is a testimony to the influence of large wood on channel morphology, channel-forming processes, and channel–floodplain connectivity (Abbe & Montgomery, 1996; Gurnell, 2012). It follows that the influence of biology can also be characterised in terms of the relative size and spatial organisation of large wood or, indeed, its absence or removal (Figure 4b).

Biological influence is, obviously, exerted by animals as well as plants. Historically, beavers were endemic to most of North America (*Castor canadensis*) and Europe (*Castor fibre*), and their effects on hydrology, hydraulics, sediment dynamics, morphology, and floodplain connectivity are known to have been pervasive (Pollock, Lewallen, Woodruff, Jordan, & Castro, 2017). In areas characterised by beaver occupation and dam building, valley morphology is often described as a "beaver meadow," indicating the intensity of geomorphic change resulting from beaver activity (Polvi & Wohl, 2012). When beavers were driven towards extinction during the late 19th century, their removal often resulted in channel degradation, disconnection from the floodplain, lowering of groundwater tables, and impoverished stream ecologies that are only now starting to recover in response to restoration projects that increasingly include beaver reintroduction or recolonisation (Pollock et al., 2017; Figure 4c).

Although the morpho-dynamic influences of large animals like beaver and wolves (Polvi & Wohl, 2012) are well known, it is easy to underappreciate the impacts of very small animals, especially when their habitats are masked. Yet recent research has established that benthic life also affects riverine processes, particularly through its impact on bed mobility. For example, colonisation of a stream by freshwater mussels (*Unionoida*) and/or macroinvertebrates such as caddisfly (*Trichoptera*) can significantly reduce bed mobility compared with that of uncolonised stream beds formed in otherwise equivalent sediments (Zimmerman & de Szalay, 2007). Conversely, bioturbation by crustaceans such as crayfish (*Astacoidea* and *Parastacoidea*) or by spawning salmon (*Onchorynchus* spp.) can increase bed mobility by disrupting the surface armour in gravel-bed rivers (DeVries, 2012; Harvey et al., 2011). It follows that the influence of biology can be characterised in the SET on the basis of the presence, abundance, and health of benthic life (Figure 4d) as well as that of riparian vegetation and mammals.

4 | MORPHO-DYNAMIC DOMAINS, STREAM CLASSIFICATION, AND STREAM EVOLUTION

4.1 | Morpho-dynamic domains

The influence axes of the process drivers describe morpho-dynamic domains within the SET, which are zones characterised by particular combinations of relative geological, hydrological, and biological influence. Because the axes are not scaled or rigidly defined and because the influences are relative, the SET can accommodate a wide range of stream classifications and evolutionary models, thus providing a flexible, conceptual "thinking space" within which to evaluate not only current channel forms but also sensitivity to disturbance, past trends of change, and possible future trajectories of adjustment. However, attempting to map the morpho-dynamic domains within the SET and populate them with typical examples, a priori would risk closing down, or at least constraining, the thinking space we seek to create. Accepting this, there is still a case for making that space a little less abstract by including here three examples of rivers that illustrate morpho-dynamic domains associated with the corners of the triangle.

An archetypal example of a stream naturally controlled by geology is the Colorado River within the Grand Canyon. In addition to being laterally constrained, the river is also hydrologically emaciated as it is regulated by multiple upstream dams. Also, the influence of biology is muted because vegetation on the floor of the canyon is sparse. Accordingly, this reach of the Colorado River plots in the geology corner of the SET (Figure 5a).

The Rakaia River, New Zealand, rises in the Southern Alps before draining across the broad expanse of the Canterbury Plains. In its middle reach, the Rakaia is geologically unconstrained, and its flow regime features highly variable discharges, including great floods driven by rainstorm, snowmelt, and rain-on-snow events. Sediment loads are high, deriving from rapid erosion in the headwater basins. Consequently, the middle reach of the Rakaia plots in the hydrology corner of the SET (Figure 5b).

The Rio Negro is a tributary to the River Amazon. Globally, it is the seventh largest river by discharge, and its lower course has created a

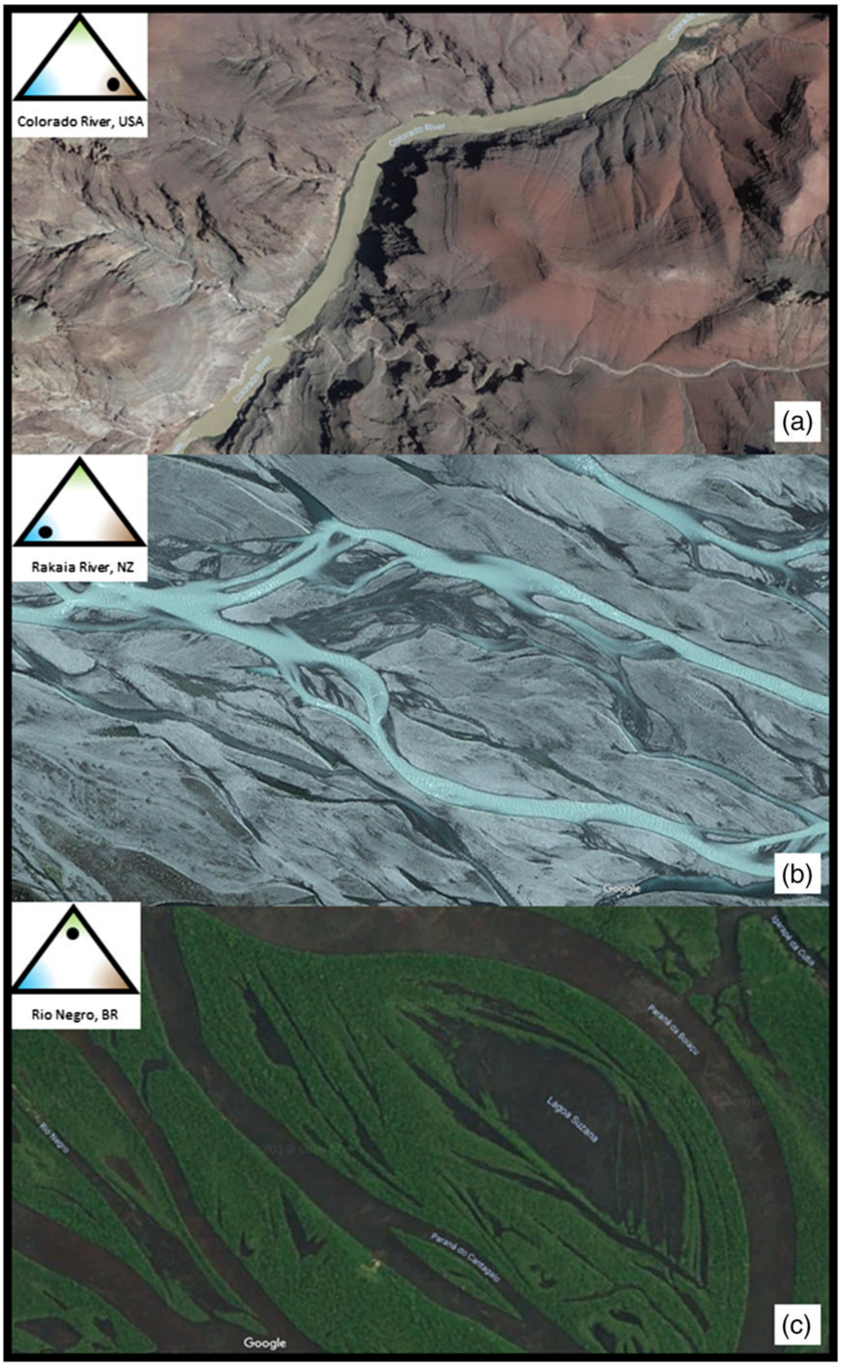

FIGURE 5 Archetypal examples of world rivers representing the three corners of the stream evolution triangle. Images from Google Maps [Colour figure can be viewed at wileyonlinelibrary.com]

continuous riparian corridor that is up to 30-km wide. On the basis of its discharge, it might be expected that the Rio Negro would plot in the hydrology corner of the SET. However, the sediment load of the Rio Negro is disproportionately small, and its planform is anastomosed, featuring an intricate network of anabranches bordered by islands and floodplains that are densely vegetated by obligate and facultative wetland species (Figure 5c). On the basis of these attributes and despite its huge discharge, form and process in the lower Rio Negro are dominated by biology, and hence, it plots at the apex of the SET.

4.2 | Stream classification

Morpho-dynamic domains within the SET have associated characteristic stream morphologies that are conventionally classified as particular channel types. In this context, the SET is able to accommodate a wide range of existing stream classifications, including those of Schumm (1985; Figure 1) and Rosgen (1996; Figure 6), which rely on physical attributes such as slope, bed material, number of channels, sinuosity, width-to-depth ratio, and confinement. Plotting these classifications in the SET provides new insights because plotting position associates stream types with the relative influences of all three process drivers. Generally, ease of adjustment decreases with proximity to any corner of the triangle, as the influence of one driver becomes controlling and, hence, the stream type becomes more persistent.

For example, in the geology corner, the morphologies of bedrock channels are highly resilient to change because their boundaries are fixed, at least over timescales of decades to centuries. In the hydrology corner, the wide, braided subchannels of alluvial rivers with abundant runoff, mobile sediments, and little or no vegetation adjust constantly, but the braided planform persists through time. Near the apex, where the influences of hydrology and geology are muted and the life of the river predominates, flows are slower, boundaries are erosion resistant, and the multiple channels are relatively small, making anastomosed planforms resilient to disturbance. In contrast, closer to the centre of the triangle, the relative influences of geology, hydrology, and biology are finely balanced. In this region of the SET, frequent adjustments to stream processes are intrinsic to the single-thread–meandering morphologies that predominate.

What the SET adds to existing classifications is explicit recognition that, when affected by multiple drivers, a stream's morphology adjusts constantly in response to fluctuations in their relative influences. In the SET, morphology and ease of adjustment are both indivisibly tied to the relative influences of the process drivers, conditioning the stream system's susceptibility or resilience to change, and its capacity for recovery or relaxation following major disturbance.

4.3 | Evolutionary pathways

Morpho-dynamic domains within the SET also have associated characteristic stream evolution stages and trajectories that occur in response to various types of disturbance. Consequently, the SET provides a

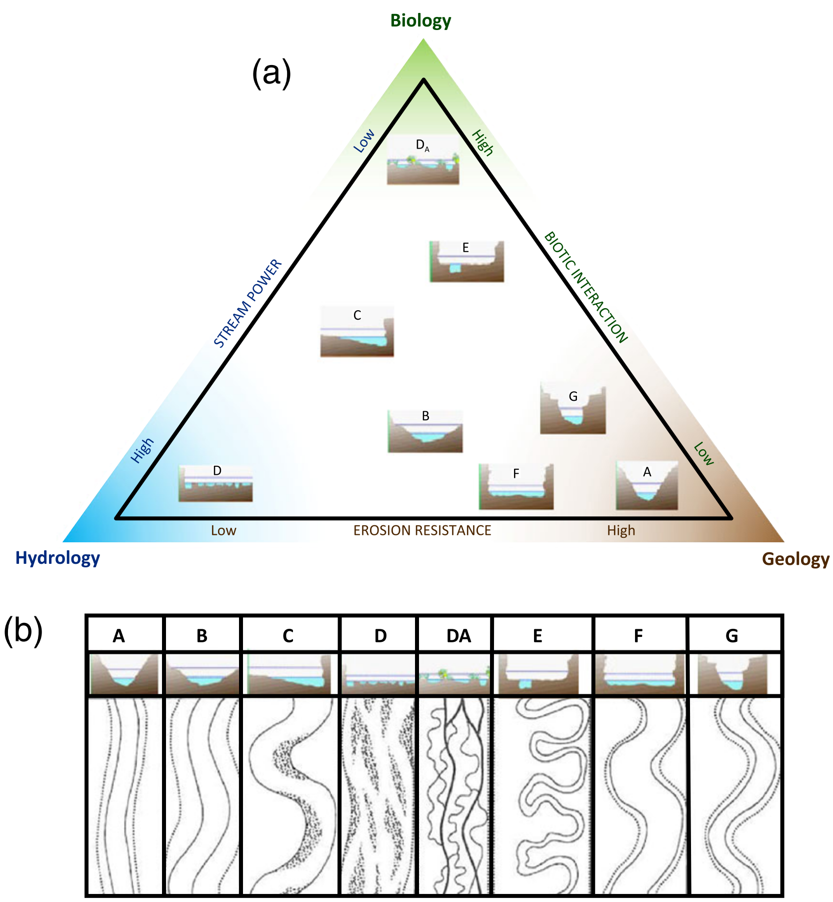

FIGURE 6 (a) Stream evolution triangle with example classification system (Rosgen, 1996); (b) Rosgen Stream Classification System (modified from Rosgen, 1996) [Colour figure can be viewed at wileyonlinelibrary.com]

suitable template for plotting the stages in channel and stream evolution models, such as that of Cluer and Thorne (2014; Figure 7).

In the original CEMs, morphological adjustments are represented as a linear sequence, whereas in the later SEM, the sequence is represented as being cyclical. Although both linear and cyclical behaviours are observed in nature, it is rare for a single site to follow the precise sequence of evolutionary stages envisaged in either the CEMs or the SEM. The advantage of plotting evolutionary stages within the SET is that this highlights the possibility of a stream following other evolutionary pathways, depending on how the relative influences of the process drivers vary through time and space during postdisturbance evolution.

In the SEM, an evolving stream passes rapidly through some evolutionary stages although it may linger in others (Cluer & Thorne, 2014). The SET captures this temporal variability because the plotting positions for different stages indicate not only their morphological form and function but also, through their proximity to a corner or the centre of the triangle, their ease of change, which governs how long an evolving stream spends in a particular evolutionary stage.

Finally, even in rapidly evolving systems, it is unusual for a given site to complete the eight-stage SEM cycle, because this requires at least a decade of undisturbed, incremental evolution and, more often than not, the cycle is interrupted, advanced, or reversed by subsequent disturbances or complex responses in the fluvial system (see Zheng, Thorne, Wu, & Han, 2017). Although the SEM's evolutionary pathway does plot coherently in the SET (Figure 7), it is no longer prescribed deterministically. In the SET, channel morphologies and evolutionary pathways are emergent properties, charted on the basis of changes in the relative influences of the high-level drivers and morphological susceptibility or resilience to change. Consequently, although some evolutionary trends are more probable than others, as in nature, a disturbed stream's evolutionary path is not predetermined. In this regard, uncertainty stemming from natural variability is inherent to the SET.

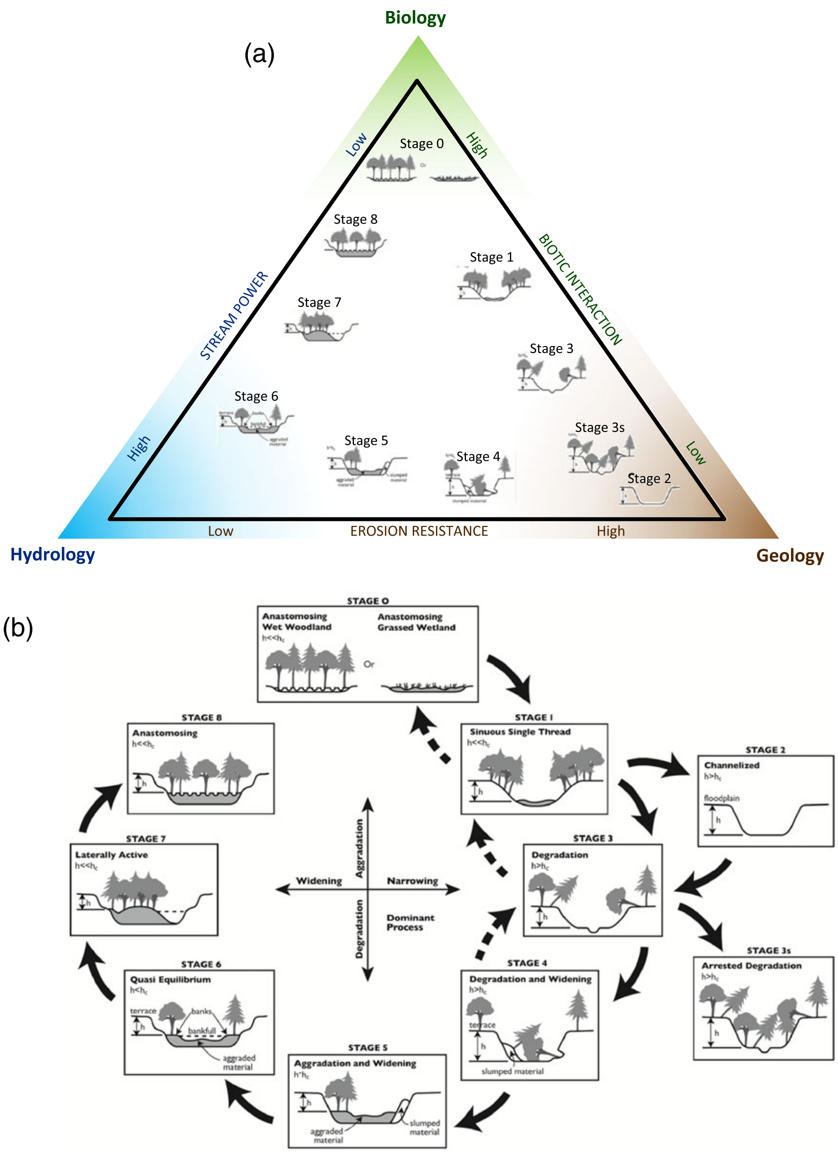

FIGURE 7 (a) Stream evolution triangle with stages of stream evolution (Cluer & Thorne, 2014); (b) stream evolution model (Cluer & Thorne, 2014) [Colour figure can be viewed at wileyonlinelibrary.com]

5 | STREAM DISTURBANCE, RESPONSE, AND RECOVERY

Fluvial geomorphology has long recognised that disturbance may result from a variety of natural events or human actions that affect catchment runoff, sediment yield, or the channel's dimensions, geometry, and resistance to flow and erosion (Knighton, 1998). In river science and management, the significance of disturbance resulting from changes to catchment, floodplain, riparian, and in-channel vegetation has been widely appreciated for decades (Thorne, Soar, Skinner, Sear, & Newson, 2010). More recently, disturbances that affect longitudinal and/or lateral connectivity in the fluvial system are receiving increasing attention (Wohl et al., 2018), whereas the importance to river forms and processes of changes to catchment, stream, and aquatic ecology is now accepted (Atkinson et al., 2018).

The SET reveals that for postdisturbance recovery to be robust and enduring, some degree of biological uplift is essential and re-establishment of a healthy and functional ecosystem (represented by migration upwards of plotting position in the SET) depends on the rate of recolonisation compared with the frequency of physical or biological disturbance (Shafroth, Stromberg, & Patten, 2002). The SET can aid understanding in both the impact of a disturbance and recovery at the reach and system scales, because it represents causal relationships between changes in the process drivers (and hence SET-defined, morpho-dynamic domains) and the types of disturbance, morphological response, and evolutionary trajectory that result. In this context,

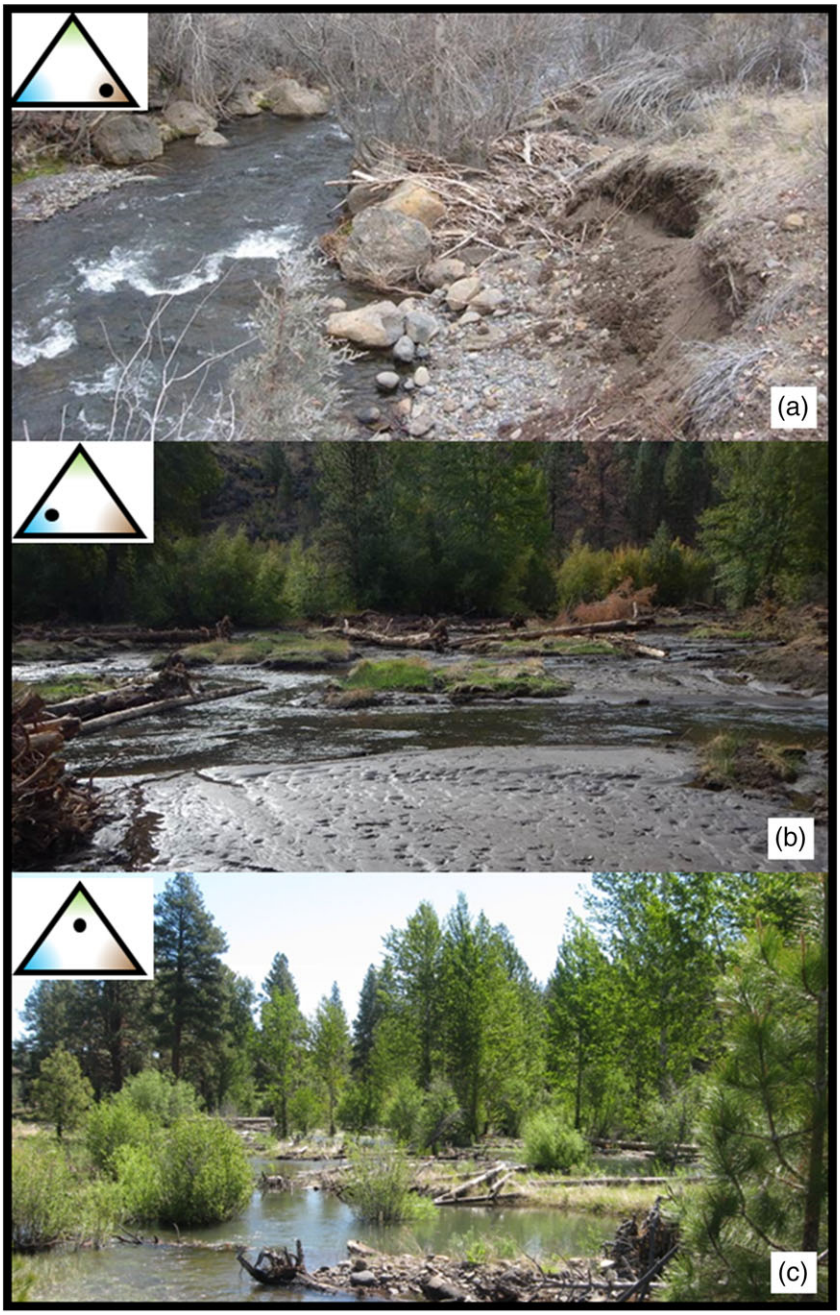

FIGURE 8 Whychus Creek, Oregon, restoration project phases over 1 year. Photos courtesy of Paul Powers [Colour figure can be viewed at wileyonlinelibrary.com]

restoration of disturbed streams should facilitate either recovery to the predisturbed condition or evolution towards a new, dynamically metastable morphology. Either pathway involves biological uplift. What restoration should avoid is locking an actively evolving stream into an artificially stable configuration using engineered structures.

If disturbance is simple and limited to one driver, such as hydrology, recovery may be relatively straightforward and even predictable using physics-based theories of complex response in alluvial systems (Hey, 1979). However, the SET illustrates that when a "game changing" natural or human disturbance triggers changes in process domains dominated by biology (through, for example, species extinctions or ecosystem collapse), profound changes in relative influence and major shifts of plotting position in the SET result. This indicates that natural recovery will be slow, convoluted, and functionally indeterminate, unless assisted by appropriate and well-designed river restoration.

That recovery to the predisturbance condition can be achieved through resetting the floodplain, and channel network is illustrated by a restoration project on Whychus Creek, Oregon. Prior to restoration, the postdisturbance-incised channel was vertically and laterally stable, plotting near the geology corner (Figure 8a). Filling the incised channel reconnected the stream to its floodplain, initially moving the system close to the hydrology corner (Figure 8b). Subsequent bar and floodplain recolonisation by wetland and riparian vegetation then shifted Whychus Creek towards the biology corner (Figure 8c), following a path close to the hydrology–biology side of the triangle.

6 | CONCLUSIONS

A conceptual model provides a space within which complex systems with unpredictable relationships and indeterminate outcomes can be assessed and evaluated to help elucidate potential trajectories of change and scenarios for possible future conditions. Conceptual models are "thinking tools," and the best outcome of a conceptual model is not a precise answer but deeper thinking. According to Fortuin et al. (2011), conceptual models help to "structure, retrieve, and construct knowledge, which thereby substantially improves the learning process."

In this spirit, the SET reframes physics-based fluvial geomorphology to acknowledge and explicitly account for the power of biology as a process driver. The SET's flexibility and inclusiveness are its greatest assets because the aim is not to constrain or supersede conventional wisdom but to expand and support thinking outside of the alluvial box when studying, managing, engineering, and restoring stream systems.

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