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The Technical Newsletter of the National Stream and Aquatic Ecology Center

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The Stream Evolution Triangle

The primary motivation for most river restoration projects, both nationally and internationally, is biologically-based ecosystem recovery, which often includes a focus on aquatic species and their habitats. In sharp contrast, the restoration community's approach to stream design has been dominated by the physical and engineering sciences. When a physics-based design is evaluated using biological criteria, there are substantial challenges in determining project success or failure, even where biologically-driven parameters, such as pool depth, provide specific design guidance. For example, is success defined physically (i.e. by the number of intact habitat structures or deep pools) or biologically (i.e. by juvenile fish densities or redd surveys)? To address this disconnect, we have created the Stream Evolution Triangle (SET; Figure 1) -- a new approach to understanding stream evolution, and

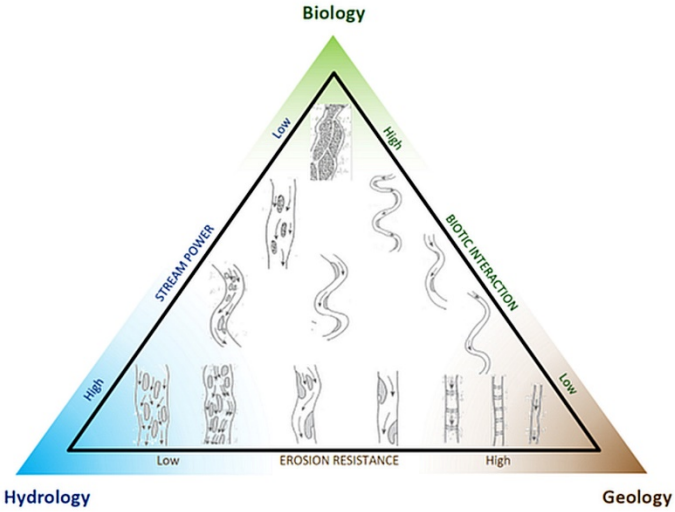

Figure 1: The Stream Evolution Triangle (SET) with planform patterns defined by Schumm (1985) illustrating typical planforms expected to occur in different process-domains. The SET represents the relative influences of geology (erosion resistance), hydrology (stream power), and biology (biotic interaction). From Castro and Thorne (2019).

StreamNotes is an aquatic and riparian systems publication with the objective of facilitating knowledge transfer from research & development and field-based success stories to on-the-ground application, through technical articles, case studies, and news articles. Stream related topics include hydrology, fluvial geomorphology, aquatic biology, riparian plant ecology, and climatology.

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hence the context for river restoration, that recognizes biology as a co-equal driver alongside geology and hydrology.

The restoration community's physics-based approach is deeply embedded not only in our design method, but in the very way that we think about stream systems. Take Lane's stream balance equation from the mid-1950s, which describes the relationship between the amount of stream flow, the slope of the channel, and the amount and size of sediment (Lane 1955; Figure 2a). Biology is not included in Lane's balance, even though we recognize the important role that biology plays in channel and floodplain formation. The idea that streamflow and slope must be balanced with sediment discharge and size to achieve equilibrium has resulted in the design of predominantly transport channels. The outcome is dictated by "equilibrium" – the avoidance of net aggradation or degradation through time. When a fundamental design parameter is sediment throughput, channels are constructed to confine flow, thus ensuring adequate shear stress and maintaining sediment transport. From a fisheries perspective, these transport channels are often important migration corridors, but do not represent the highest quality spawning and rearing habitat that is generally found in lower gradient, depositional reaches. Many stream restoration projects occur in these depositional (aggrading) valleys, where biological processes are more dominant, and hence there is a higher potential for biological uplift (Figure 2b).

In a similar vein, stream classification systems and evolution models that are commonly referenced in river restoration design (Montgomery and Buffington 1993; Rosgen 1996; Schumm et al. 1984; Simon and Hupp 1986; Cluer and Thorne 2013), do not explicitly include biology as a primary driver of stream process and form. Biology is often described as an outcome of physical processes, rather than a co-equal driver. This frame of reference – physics as the driver and biology as the product – has led to a paradigm that is biased against the power of biology (Johnson et al. 2019). By treating geology, hydrology, and biology as co-equal process-drivers, the SET challenges the current paradigm by explicitly recognizing the power of biology. This establishes that a stream may be dominated by any of these three drivers depending upon landscape setting and geographic location. This is clearly illustrated by plotting the classic planform types of Schumm (1985) on the SET (Figure 1). While Schumm (1985) did not include biology as an explanatory variable in his planform diagram (Figure 3), it is apparent from the plotting position on the SET, that biology, and vegetation in particular, is a dominant driver for several of the "Schumm" planform types.

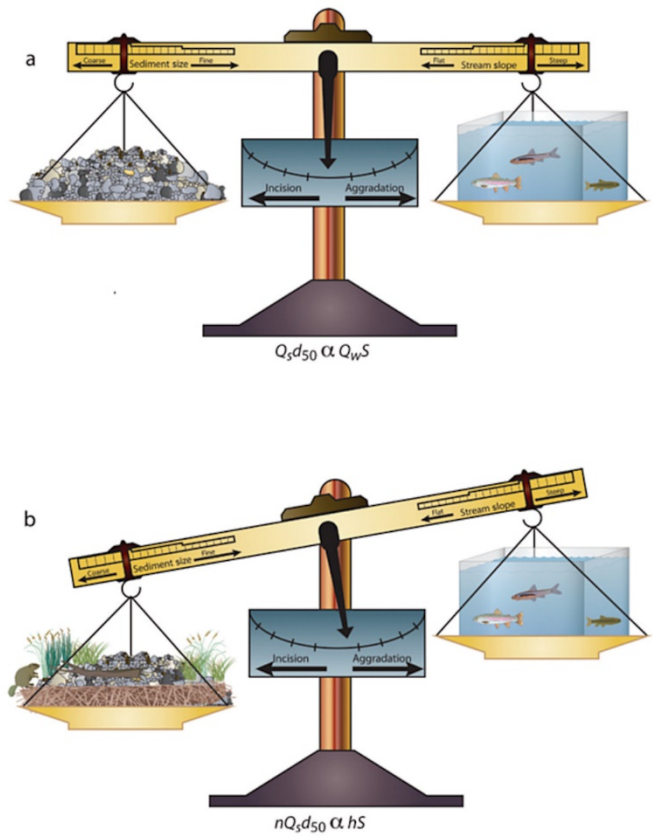

Figure 2: Lane's balance as modified by Pollock et al (2014), where (a) illustrates the physics-based relationship between stream slope and discharge to sediment discharge and caliber, and (b) illustrates the influence of biologic processes on stream aggradation/degradation.

In unequivocally recognizing biology as a co-equal process-driver, the SET expands the lens through which hydraulic engineers, hydrologists, and geomorphologists view rivers. This transition, from a physics-based science perspective, to a multifaceted perspective that integrates biological processes, allows for a deeper understanding of dynamic stream adjustments and resultant planforms. While the balance between hydrology and geology as conceptualized by Lane

(1955) forms the base of the Stream Evolution Triangle, along which biological influence is nominal, the addition of biology as the apex of the SET - where biology is the dominant driver - creates two additional axes. This allows for a full suite of stream types that includes those particular planforms that are dependent on biological processes (Davies and Gibling 2009; Ward et al. 2000).

While the SET can be applied to stream restoration planning and design in multiple ways, we provide three examples here for illustrative purposes. First, the SET provides a clearer understanding of the relationship between morphological stream stages. This allows for the selection of restoration strategies that address both adverse impacts from past disturbance, and increased resilience to future disturbances. Second, the SET provides a framework in which restoration trajectories can be evaluated that are not limited by a linear or circular pathway. In this regard, all pathways are available, but some are more probable than others due to the relative influence of geology, hydrology, and biology. And third, the SET can be used to evaluate progress towards project goals through time, while also allowing for the incorporation of future disturbances. Given the variety of spatial and temporal disturbance scales and types, the SET is uniquely placed to accommodate this variability precisely because it is non-scalar and does not dictate explicit pathways for morphological adjustment of stream systems.

While the initial SET was developed to encompass natural disturbances and stream evolution, modifying the SET to explicitly incorporate human modifications is relatively straightforward (Figure 4).

Although not all management actions, such as reconnecting floodplains, will result in the exact same plotting positions on the SET, it is possible to evaluate the relative influence of the drivers for a given landscape setting and the resultant position for specific management intervention. This is useful when evaluating either the benefits or impacts of a proposed stream project, such as channel stabilization, instream gravel mining, or management of invasive species (Figure 5).

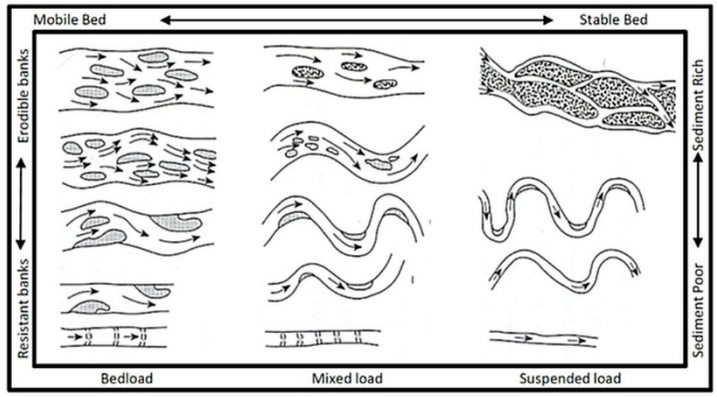

Figure 3: Planform patterns as defined by Schumm (1985), modified from Knighton (1998).

From a stream restoration perspective, ecological recovery requires some degree of biological uplift and re-establishment of a healthy and functional ecosystem (represented by upward migration in the SET), which depends on the rate of biological recolonization compared to the frequency of physical or biological disturbance (Shafroth et al. 2002). The SET can aid understanding in both the impact of a disturbance and recovery at the reach and system-scales, because it represents linkages between process-drivers, disturbance types, morphological responses, and evolutionary trajectory. Thus restoration of impacted streams should facilitate either recovery to the pre-disturbed condition or evolution to a new, resilient morphology. Either pathway involves biological uplift. What restoration should avoid is locking a disturbed stream into an artificially stabilized form.

Restoration of Whychus Creek in central Oregon (StreamNotes, June 2015) illustrates the potential for

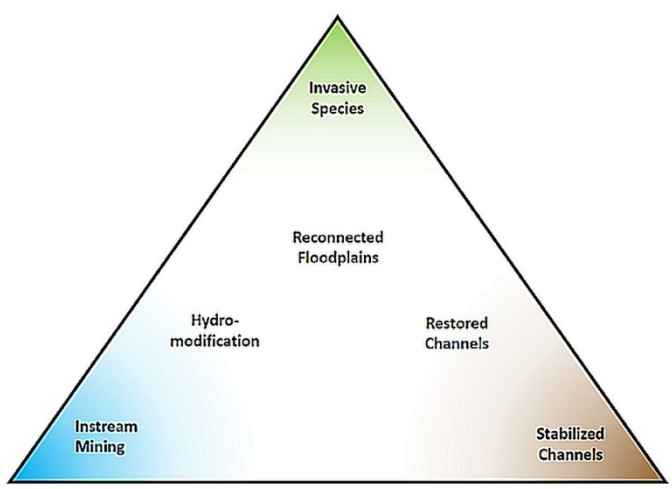

Figure 4: Approximate plotting position of human-modified stream systems.

rapid biological uplift achieved through full reconnection of the channel/floodplain network. Whychus Creek, like many small to moderate-size streams, was ditched and moved to the edge of its alluvial valley to increase available arable land and to allow for the efficient routing of irrigation water. In its unrestored, incised condition, Whychus Creek plots near the Geology corner (Figure 6a) due to its erosion resistant bed and banks. Intentional filling of the incised channel, as part of a full floodplain-channel-wetland restoration project, reconnects the stream to its floodplain, and moves the system towards the Hydrology corner immediately following construction (Figure 6b). Natural colonization by aquatic, wetland and riparian plants and animals then begins to shift Whychus Creek upwards towards the Biology corner (Figure 6c), following a path along the Hydrology-Biology edge of the triangle. This recovery trajectory, from Geology over to Hydrology, and upwards towards Biology, appears to hold for many stream restoration projects. This is due to our ability to construct desirable "landforms", such as channels, bars and pools, and our inability to build "habitat", such as a mature riparian forest, which evolves and develops through time.

In summary, the purpose of the Stream Evolution Triangle is to create an expansive 'thinking space'. It does not exclude or supersede any evolutionary models or stream classification systems. However, because the most commonly used stream classification systems and evolution models implicitly assume that river form is derived from physical interactions between the streamflow, sediment, and boundary materials, their explanatory capacity is limited given the significant influence of biology in many of our stream systems, and in most of the streams that we seek to restore. Hence, in the SET, we cast biology as an equal partner with geology and hydrology, forming a triad that produces a resultant stream morphology, drives morphological adjustment, and constrains the paths along which disturbed streams evolve. The SET thus recognizes that the form, function, and evolutionary trajectory of a river system may be dominated by a single driver, a pair of drivers, or (more commonly) a combination of all three, depending on the watershed and land management contexts.

Figure 5: Human modified stream environments, including: (a) biological control due to invasive reed canary grass; (b) geological control due to artificial concrete lining; and (c) hydrologic control due to active gravel mining (removal of both vegetation and sediment).

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Management Implications

- The **Stream Evolution Triangle** is a new approach for understanding stream evolution, that recognizes biology as a co-equal driver alongside geology and hydrology.
- This concept provides a context for stream restoration.
- Because streams evolve through time, restoration actions should avoid locking an evolving stream into a stable configuration.
- This Stream Evolution Triangle:
  - informs expectations of probable "stream states" or morphologies given the relative influence of primary drivers, and provides a monitoring framework for tracking these stream adjustments, either natural or restoration-induced, through time;
  - describes why vegetation is critical to stream restoration success, and why beaver and other aquatic species may be just as important as the sediment and water in some stream systems; and
  - explains why there is more variability in hydraulic and sediment transport models in biologically-dominated systems.

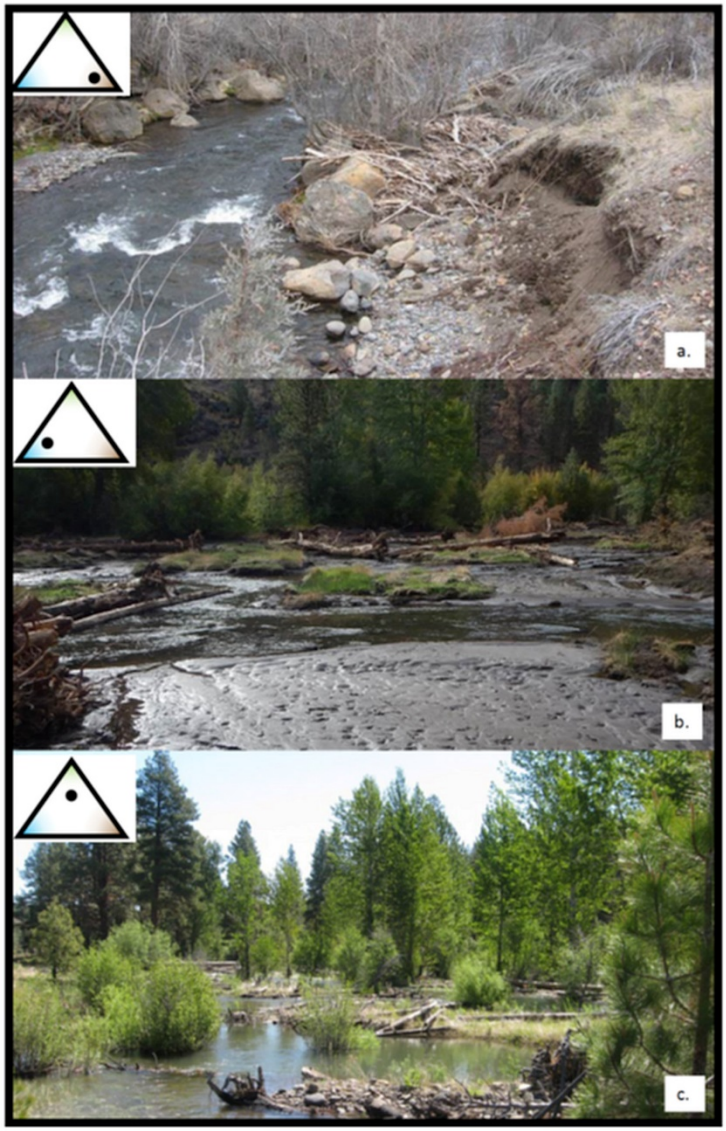

Figure 6 Whychus Creek, Oregon, restoration project phases over one year (StreamNotes, June 2015). Photos courtesy of Paul Powers, from Castro and Thorne (2019).

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Notices and Technical Tips

- **Direct technical assistance from applied scientists at the National Stream and Aquatic Ecology Center** is available to help Forest Service field practitioners with managing and restoring streams and riparian corridors. The technical expertise of the Center includes hydrology, fluvial geomorphology, riparian plant ecology, aquatic ecology, climatology, and engineering. If you would like to discuss a specific stream-related resource problem and (if needed) arrange a field visit, please contact a scientist at the Center or David Levinson, the NSAEC program manager.

- New SPARROW (SPAtially Referenced Regression On Watershed attributes) models and interactive mappers are available through the U.S. Geological Survey. These models estimate the quantity of contaminants released from watersheds by linking water quality and quantity monitoring data with watershed characteristics and contaminant sources. The interactive tools allow users simple access to "explore relations between human activities, natural processes, and contaminant transport."

  Integration of monitoring and modeling is critical to our future understanding and management of the Nation's water quality. Monitoring is the direct observation, often over time, of water-quality properties and characteristics, and models are tools for interpreting these observations.

- Are Beavers Nature's "Little Firefighters"?

  *When a wildfire tears through a landscape, there can be little left behind. A new study, though, suggests that beavers may be protecting life around streams, thanks to their signature dams. Satellite images from five major wildfires in the United States revealed that corridors around beaver habitat stayed green even after a wild*fire.

Managing for Large Wood and Beaver Dams: A New General Technical Report

Streams are dynamic ecosystems. More than a century of wood and beaver removal from streams has created a widespread perception that these features are relatively rare, and undesirable or hazardous (Chin et al., 2008), but extensive scientific research firmly supports the critical ecosystem services provided by large wood and beaver dams (Wohl, 2017). A new Rocky Mountain Research Station General Technical Report, Managing for Large Wood and Beaver Dams in Stream Corridors (Wohl et al., 2019), presents guidelines for evaluating the potential environmental benefits versus potential hazards associated with logjams and beaver dams, for more informed land management.

Managing for Large Wood and Beaver Dams in Stream Corridors has the following primary sections:

A. Review of Environmental Benefits and Potential Hazards of Large Wood and Beaver in Stream Corridors
B. Existing Work on Retention, Restoration, and Reintroduction of LW and Beaver Dams
C. Guidelines for Identifying Stream Segments that Maximize Environmental Benefits
D. Field Examples for Application

After the comprehensive summary on large wood and beavers provided in Section A, including details on benefits and hazards, Section B discusses stream management and restoration strategies, and Section C provides multi-stage (Level I and II) procedures for evaluating the retention or reintroduction of large wood and beavers. Section D is composed of field examples from across National Forest System lands.

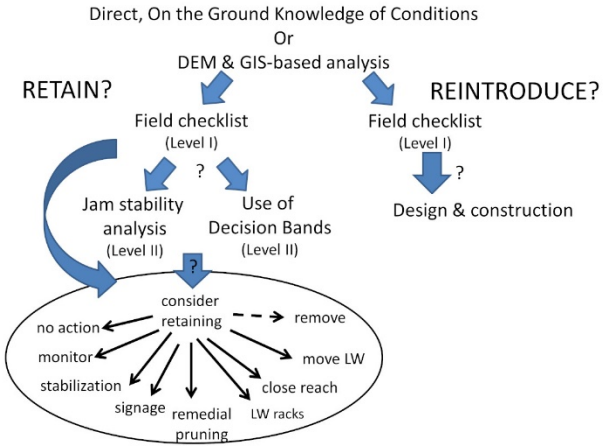

Figure 7: Schematic illustration of multi-step decision process for assessing logjams. Question marks indicate potential alternative scenarios.

We present Level 1 field checklists to evaluate two scenarios each for logjams and beaver dams: retention of an existing jam (Figure 7; Wohl et al., 2016) or dam, and reintroduction of large wood or beaver. Alternatively, GIS tools can be used to combine DEM analysis with other data such as infrastructure, recreational use, and vegetation characteristics to identify stream segments where jams and dams have a high potential for enhancing ecological function while posing acceptably little hazard, and could be managed cost-effectively (Figure 8; Wohl et al., 2017). Level II methods include force-moment analyses for logjam retention, the Wood jam Dynamics Database and Assessment Model (WooDDAM), a decision band score sheet for management decision making regarding large wood hazards (Figure 25 in Wohl et al., 2019), and the Beaver Restoration Assessment Tool (BRAT; Macfarlane et al. 2017). The checklists, WooDDAM, and the decision band score sheet are designed to be simple in application and reproducible among operators.

WooDDAM is a tool for understanding and predicting wood jam change through time (Scott et al., 2019; StreamNotes, October 2019). WooDDAM incorporates a machine-learning based statistical analysis to predict wood jam dynamics using a public database of wood jam characteristics and dynamics. The purpose of the model is to provide interpretable predictions of wood jam dynamics, based on region-specific environmental characteristics, channel characteristics, and the characteristics of specific wood jams. The model is evolving because it is based on continuing data inputs from users, and the predictions the model generates are informed by the database it is paired to; the model will evolve as users submit data to it. The database and model are designed to be used within specific environmental contexts. WooDDAM also provides a standardized survey protocol to survey wood jam characteristics and resurvey wood jams to measure wood jam dynamics. This survey protocol is designed to facilitate the contribution of data to the database. WooDDAM is available through the USDA Forest Service's National Stream and Aquatic Ecology Center website (Wood Jam Dynamics).

Stream management in diverse regions of the United States and the world increasingly emphasizes retaining or actively reintroducing

large wood (Large Wood National Manual) and beavers (Beaver Restoration Guidebook) to streams. Developing trends with respect to large wood (Roni et al., 2015) include increasing use of soft placement techniques that allow some wood movement rather than anchoring wood in place (Deer Creek story map; StreamNotes, May 2018) and passive recruitment of wood from natural source areas. Wood reintroduction is likely to be most effective when wood is placed in locations where channel geometry and hydraulics favor stability and where additional wood is likely to accumulate (Wohl et al., 2019). Monitoring wood and employing monitoring results in adaptive management can usefully inform future wood reintroduction efforts.

Developing trends with respect to using beaver dams in stream management (Pollock et al., 2014, 2017) include modeling habitat suitability and carrying capacity to evaluate the ability of a stream segment to support beaver populations (Macfarlane et al., 2017) and actively reintroducing beavers. Beaver dam analogs are increasingly being constructed (Pollock et al., 2012; Bouwes et al., 2016), either in lieu of actual beavers in situations where the animals cannot survive, or as a precursor to return of beavers to a site. Where the presence of beavers and their dams can create hazards or nuisances, simple techniques such as pipes to maintain backwater ponds below a threshold water level or fencing around culverts can be used to reduce the negative effects of beaver activities (Lisle, 2003).

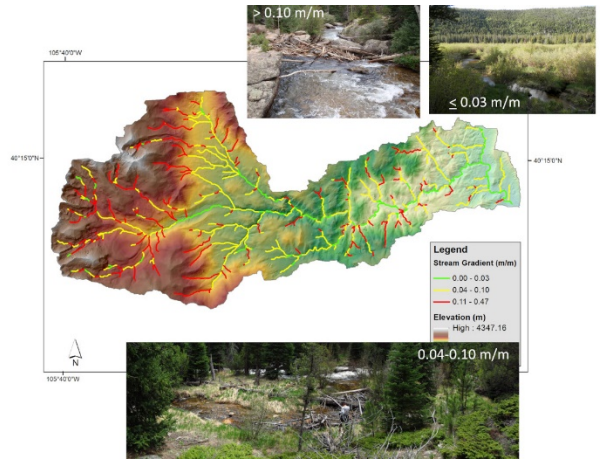

Figure 8: Example of applying the DEM-based analysis of stream gradient segments within a watershed. Map of segment-scale stream gradient in three categories in the North St. Vrain Creek watershed, Colorado. Inset photos illustrate channel and valley geometry characteristic of each gradient class.

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