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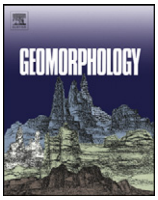

Editorial

Introduction to the special issue on discontinuity of fluvial systems

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ABSTRACT

Fluvial systems include natural and human-created barriers that modify local base level; as such, these discontinuities alter the longitudinal flux of water and sediment by storing, releasing, or changing the flow path of those materials. Even in the absence of distinct barriers, fluvial systems are typically discontinuous and patchy. The size of fluvial discontinuities ranges across scales from 10^0 m, such as riffles, to 10^4 m, such as lava dams or major landslides. The frequency of occurrence appears to be inversely related to size, with creation and failure of the small features, such as beaver dams, occurring on a time scale of 10^0 to 10^1 years and a frequency of occurrence at scales as low as 10^1 m. In contrast, larger scale discontinuities, such as lava dams, can last for time scales up to 10^5 years and have a frequency of occurrence of approximately 10^4 m. The heterogeneity generated by features is an essential part of river networks and should be considered as part of river management. Therefore, we suggest that “natural” dams are a useful analog for human dams when evaluating options for river restoration. This collection of papers on the studies of natural dams includes bedrock barriers, log jams and beaver dams. The collection also addresses the discontinuity generated by a floodplain — in the absence of an obvious barrier in the channel — and tools for evaluation of riverbed heterogeneity. It is completed with a study of impact of human dams on floodplain sedimentation. These papers will help geomorphologists and river managers understand the factors that control river heterogeneity across scales and around the world.

River networks are typically patchy and discontinuous systems (Montgomery, 1999), where patches are formed by the fluvial or “extrafluvial” (sensu Ely et al., 2012) processes that generate fluvial discontinuities. These discontinuities are often distinct barriers to water and sediment transport that modifies local base level, which has long been recognized as an important component of the fluvial system (Mackin, 1948). Fluvial discontinuities alter the longitudinal flux of water and sediment by storing, releasing, or changing the flow path of those materials. They can disrupt the progression of a river toward a graded system (sensu Gilbert, 1877) by delaying river incision at time scales up to 10^4 to 10^5 years (Ely et al., 2012). Conversely, the catastrophic floods that may accompany the failure of fluvial barriers generate rapid incision that is far in excess of the flooding that would be generated by meteorological conditions alone (Butler and Malanson, 2005; O'Connor and Beebee, 2009); these are recognized as flood hazards critical to river management (Costa and Schuster, 1988). The effects of natural dams are sufficient to control valley formation, where the scale of impact varies according to the scale of the barrier (e.g., Korup et al., 2010; Kramer et al., 2012).

Even without the presence of distinct barriers, the patchiness of river networks is best described as a discontinuum (Poole, 2002). By generating storage and release of water, discontinuities increase the complexity of flow paths across and along the river corridor, modifying temperature and biogeochemical regimes. These effects generate longitudinal and lateral heterogeneities of instream and riparian habitats across river networks (Burchsted et al., 2010). Given the importance of discontinuity on river form and function, it should be assessed as part of river management (Brierley et al., 2002; Snyder et al., 2009); however, river restoration often relies on the dominant ecological paradigm of the River Continuum Concept (Vannote et al., 1980) when evaluating human impacts on rivers (e.g., Hart and Poff, 2002). This special issue further examines the impact of specific fluvial discontinuities on river form and process and also presents tools for evaluation of discontinuity and heterogeneity.

Here, we start by categorizing discontinuities as those generated by living, dead, and non-living material and agents. We refer to the ones generated by non-living materials and agents as abiotic discontinuities. These span a wide range of spatial and temporal scales. At the smallest scale, they include features such as riffles and they are typically generated by autogenic fluvial processes. Examples of abiotic discontinuities at the largest scale include major ice and sediment dams, lava dams, and landslides, all of which tend to be extrafluvial. In contrast, biotic discontinuities are formed by living

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or dead material or by living agents. Beaver dams, wood jams, and "livewood" barriers (sensu Opperman et al., 2008) are all examples of biotic discontinuities. These barriers are also extrafluvial; further, they require additional ecological understanding to assess controls and impacts. In contrast with abiotic barriers, biotic barriers are found nearly exclusively at smaller spatial and temporal scales. Dams and other barriers constructed by humans would fall within this category; however, river restoration typically compares the impacts of human-built dams with free-flowing rivers (e.g., Stanford and Ward, 2001). Instead, we suggest that the discontinuity generated by "natural" dams serves as a better analog of baseline channel form and function when assessing the impacts of human-constructed barriers.

Classification and assessment of the many types of discontinuities in fluvial systems should address spatial scale, longevity and recurrence interval, and spatial and temporal frequencies of the patches. In that context, large-scale discontinuities can clearly modify river networks at significant scales. These features tend to be infrequent over space and time, at frequencies of tens of kilometers and longevities that can reach 10^5 years (Ouimet et al., 2007; Korup et al., 2010). Small-scale discontinuities, on the other hand, can be extremely frequent, with construction and failure on a time scale of 10^0 to 10^1 years and a frequency of occurrence at scales as low as 10^1 m (Burchsted et al., 2010; Wohl and Beckman, 2013-this issue).

The spatial scale of the impact of discontinuities and the frequency of occurrence over space are likely inversely related. Similarly, the duration of a discontinuity and the scale of aggradation of sediments appear to be directly related (e.g., Ely et al., 2012; Polvi and Wohl, 2012). In contrast with large-scale discontinuities, which would be expected to create few, infrequent large patches visible only at large scales, small-scale discontinuities would be expected to generate high variability in headwaters but be less effective at higher stream orders, although notable exceptions may occur (e.g., Collins and Montgomery, 2002).

To apply an assessment of discontinuity to river management and restoration, it is useful to consider the historic range of variability (Wohl, 2011)). Within that context, we can expect that barriers of various types have been in river corridors over geologic time; the historic range of variability incorporates the range of conditions generated by these barriers. If maintenance of existing biological communities and species is desired, it is reasonable to think that they are adapted to the range of conditions generated by natural discontinuities. Ecological data support the importance of this type of heterogeneity (e.g., Schlosser, 1995). Therefore, it is useful to compare the functions of human-generated discontinuities with the other types.

Functions generated by discontinuities include those generated during active blockage of the channel as well as those generated during failure and following failure. The impacts of an intact natural dam are somewhat comparable to a human dam in terms of reduced water velocity, decreased channel gradient and sediment size, and increased aggradation rates. In general, natural discontinuities are longer than human ones in the direction of water flow, with lengths at scales of 10^1–10^4 m (Burchsted et al., 2010; Korup et al., 2010). They are usually less substantial, with flow frequently traveling through rather than over the substrate. In addition to being leaky, natural barriers are heterogeneous across the channel, setting a variable water level behind the barrier that creates heterogeneity of habitat in the impoundment; this contrasts with the homogeneous cross-section and habitat of human-built barriers and corresponding impoundments. Unlike the human-built analogs, natural dams commonly force the river to bypass the barrier, generating lateral and downstream erosion and aggradation that create distinct channel forms and habitats (Westbrook et al., 2006, 2011; Ely et al., 2012).

The differences between human and natural dams can be even greater when considering the failure of these dams. Where catastrophic failure of human-built dams is often tragic and avoided at nearly all costs, catastrophic failure of natural dams is a regular occurrence. Considering that beaver dams often fail within a decade of construction (Fryxell, 2001), the historic range of variability includes frequent, stochastic channel-shaping floods far in excess of the number predicted by meteorology alone. Not all natural dams fail catastrophically, however, and the dams themselves may breach only once the impoundment is filled with sediment, if at all (Ely et al., 2012; Burchsted and Daniels, 2013).

The papers in this collection address the range of discontinuities in fluvial systems that can better define targets of river management. Abiotic barriers are discussed in two papers (Grenfell et al., 2013-this issue; Toone et al., 2013-this issue), both of which discuss bedrock controls on channel form at large scales. Biotic barriers are discussed in three papers (Levine and Meyer, 2013-this issue; Wohl and Beckman, 2013-this issue; Burchsted and Daniels, 2013), one of which discusses log jams and two of which address beaver dams. Four papers discuss the patchiness of fluvial systems that is generated without obvious barriers (Helton et al., 2013-this issue; Legleiter, 2013a,b-this issue; Nelson et al., 2013-this issue), one of which addresses flow path complexity generated by floodplains. The other three papers in this group address modeling and visualization approaches for characterizing streambed patchiness. These techniques also have potential for application to reaches with barriers. The collection is completed with one paper that addresses the discontinuity generated by human dams (Renshaw et al., 2013-this issue).

The papers that discuss abiotic barriers highlight the importance of hydrologic regime and sediment supply on the channel form that is generated by these barriers. Toone et al. (2013-this issue) use aerial photography and channel bed surveys to analyze the evolution of channel form from 1928 to 2006 on 5 km of the Drôme River in southeast France. They show that the impact of a bedrock control varies according to the sediment supply and flood frequency. As sediment supply and flood frequency decrease, the river straightens and incises, losing the complexity of its braided form and becoming disconnected from its floodplain. Grenfell et al. (2013-this issue) compare channel form in two climatically different but geologically similar basins in South Africa. These basins have similar headwater valley fills and, downstream, the floodplains have similar dolerite bedrock controls. Despite these similarities, the two floodplains are distinctly different. The Seekoei River floodplain — subject to a semi-arid climate with highly seasonal rainfall — has multiple threads and frequent avulsions that incise the bedrock. In contrast, the Nsonge River floodplain — subject to a sub-humid climate with regular rainfall — has a meandering river set within a wide floodplain, where a veneer of valley fill rests on top of a bedrock surface that has been flattened by lateral planation. Both of these papers highlight the importance of temporal and spatial contexts in predicting the impacts of discontinuities and in managing rivers.

The discussions of biotic barriers are set at similar scales as the discussions of abiotic barriers, but many more biotic barriers are found within the scale of analysis. Wohl and Beckman (2013-this issue) examine channel and valley form across scales in the North St. Vrain Creek network in the Colorado Front Range, USA. At basin scales, they show that forest composition controls the volume of wood available for log jams. Bedrock variation is an additional control at this scale, where valley widths alternate between wide and narrow: width correlates with joint spacing of bedrock outcrops. At reach and unit scales, log jams are significant controls on the presence of fine sediment and organic material. The paper also demonstrates the importance of allogenic forcing in the response of instream barriers; in this case, land use has decreased the ability of the river to retain wood even when wood is available in the riparian forest, resulting in the loss of fine sediments and organic material from modern river systems in comparison with the historic range of variability.

The examination of log jams is complemented by the papers that examine beaver dams, which show that these barriers also act as reach-scale controls on channel form. Burchsted and Daniels (2013) compare sediment size and channel shape in beaver ponds and free-flowing reaches in several rivers in Connecticut, USA. The dams in this study affect downstream reaches as well as the upstream ponds. This paper presents evidence for erosion within impoundments; this evidence suggests further discontinuity at smaller scales, where portions of the impoundments are aggrading adjacent to others that are incising. The authors conclude with a classification scheme to assess the impacts of beaver dams on headwater river networks, where impoundments, free-flowing reaches, and failed impoundments are considered as fundamental classes. Existing classification schemes (e.g., Montgomery and Buffington, 1997) are set within the free-flowing class, and additional subclassification is suggested for the impoundment and failed impoundment classes. Similarly, Levine and Meyer (2013-this issue) assess sediment texture and volume of fine sediment deposits upstream of active and breached beaver dams and in undammed reaches on Odell Creek, which flows down a fluvial fan, in Red Rock Lakes National Wildlife Refuge, Montana, USA. They show that impounded sediments are mobilized by high flows and that the majority of impounded sediments are mobilized when the dam breaches. Nonetheless, the sediments that remain following a dam breach continue to modify channel form and floodplain development.

In contrast with the studies of natural dams, Renshaw et al. (2013-this issue) analyze the impact of human-built and managed dams on floodplain connectivity. They examine the lateral distribution of ^{210}Pb — a short-lived fallout radionuclide — across the river and floodplain of five regulated and unregulated river reaches in Vermont, USA; they use the ^{210}Pb distribution as an estimate relative rate of sedimentation. They show that the pattern of sedimentation remains similar regardless of the presence of upstream dams: ^{210}Pb inventories are low immediately adjacent to the channel, increase to peak values as flood inundation frequencies begin to decrease, and then decrease asymptotically as inundation frequencies continue to decrease until the inventories reach the equilibrium value associated with atmospheric deposition. This pattern contrasts with the hypothesized relationship between distance from the channel and rate of sedimentation. Although the relationship between inundation frequency and sedimentation pattern applies across the regulated and unregulated reaches, the reaches that are downstream of the human-managed dams have a narrower band of sedimentation and less sedimentation overall. The authors suggest that the similarities in sedimentation patterns result from regional sediment limitations and channel stability.

Helton et al. (2013-this issue) present an example of fluvial discontinuity that is not generated by a barrier to longitudinal flow. They use spatially explicit, three dimensional modeling with particle tracing to analyze flow paths in the Nyack Floodplain in Montana, USA. Their results show the importance of coupling between the floodplain and river channel. In this case, the relationship between hydrologic residence time and discharge varies according to whether the floodplain is directly connected or disconnected to the channel. When flow remains within the channel banks, residence time decreases with increasing discharge; after the banks flood, residence time increases with discharge. Further, including subsurface water in the calculations of residence time reveals different patterns than analysis of surface water alone; residence time decreases by an order of magnitude and flow rates decrease exponentially with discharge because of the effects of subsurface storage. These findings emphasize the importance of assessing river discontinuity laterally across the channel cross-section and vertically through the streambed in addition to examining the impact of longitudinal barriers.

This collection of papers includes two tools for evaluation of the extent of discontinuity and associated patchiness. Nelson et al. (2013-this issue) apply four clustering algorithms to identify patches on the gravel bed generated by a flume experiment at St. Anthony Falls Hydraulic Laboratory, USA. They use the clustering algorithms on a high-resolution plan view grid of grain-size distribution along a 24 m-long section of the 80 m-long flume, where the grid is generated through image analysis of photographs of the dewatered flume following experimental runs. They also visually identify patches and compare them with the clustering results. Their results show improved separation of patches by all of the clustering algorithms in comparison with visual identification. Additionally, these techniques eliminate the subjectivity that is part of visual identification. Although the image collection technology necessary for this analysis can only be used in the laboratory flume environment, continued technological improvements may allow for the use of these methods in the field. A complementary technique for analysis of heterogeneity is presented by Legleiter (2013a,b-this issue), who evaluates the variability of bed topography in contrast to the grain size analysis of Nelson et al. Legleiter first develops a geostatistical framework to characterize reach-scale variability (2013a-this issue). He then applies that framework to analysis of a restored channel reach on the Merced River, California, USA, and to three river reaches in Yellowstone National Park, USA (2013b-this issue). Legleiter's framework relies on dimensionless analysis of channel form: distances along the channel are scaled by mean channel width, and elevation residuals of the elevation vs. distance regression are scaled by mean bankfull depth. Analysis is conducted with a variogram, which expresses difference in observed values as a function of the distance between observations. This framework allows for visualization of the heterogeneity of channel reaches and relies on spatially dense topographic data that can be collected in the field.

In conclusion, discontinuities are a major control on river shape and function, including those of particular importance to people. Although billions of dollars are being spent to restore river systems, discontinuity is generally overlooked as a part of the baseline condition. Given the emphasis on the free-flowing channel in river restoration and management, an improved understanding of discontinuity in fluvial systems is critically needed. The studies and tools in this volume help guide this needed research and management, improving our understanding and management of river systems across the USA and the world.

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