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Predicting the type, location and magnitude of geomorphic responses to dam removal: Role of hydrologic and geomorphic constraints

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ABSTRACT

Using a dam removal on the Ashuelot River in southern New Hampshire, we test how a sudden, spatially non-uniform increase in river slope alters sediment transport dynamics and riparian sediment connectivity. Site conditions were characterized by detailed pre- and post-removal field surveys and high-resolution aerial lidar data, and locations of erosion and deposition were predicted through one-dimensional hydrodynamic modeling. The Homestead Dam was a ~200 year old, 4 m high, 50 m wide crib dam that created a 9.5 km long, relatively narrow reservoir. Following removal, an exhumed resistant bed feature of glaciofluvial boulders located 400 m upstream and ~2.5 m lower than the crest of the dam imposed a new boundary condition in the drained reservoir, acting as a grade control that maintained a backwater effect upstream. During the 15 months following removal, non-uniform erosion in the former reservoir totaled ~60,000 m^3 (equivalent to ~9.3 cm when averaged across the reservoir). Net deposition of ~10,700 m^3 was measured downstream of the dam, indicating most sediment from the reservoir was carried more than 8 km downstream beyond the study area. The most pronounced bed erosion occurred where modeled sediment transport increased in the downstream direction, and deposition occurred both within and downstream of the former reservoir where modeled sediment transport decreased in the downstream direction. We thus demonstrate that spatial gradients in sediment transport can be used to predict locations of erosion and deposition on the stream bed. We further observed that bed incision was not a necessary condition for bank erosion in the former reservoir. In this characteristically narrow and shallow reservoir lacking abundant dam-induced sedimentation, the variable resistance of the bed and banks acted as geomorphic constraints. Overall, the response deviated from the common conceptual model of knickpoint erosion and channel widening due to dam removal. With thousands of dams likely to be considered for removal or repair in the coming decades, this study helps to advance predictions of the geomorphic response to dam removal and contributes to a broader understanding of the variability in both style and timing of fluvial responses to disturbances.

1. Introduction

Following an era of dam building that peaked in the 1960s, the U.S. is now entering an era of increasing dam removal or repair as the majority of the ~80,000 large and medium sized dams (Graf, 1999) are reaching the end of their ~50 year design lifespan (Shuman, 1995; Maclin and Sicchio, 1999). Many of these dams are no longer needed for the original uses, and the benefits of undammed rivers for aquatic resources and riparian habitat are becoming increasingly understood and valued (Nilsson and Berggren, 2000; Bednarek, 2001; Bushaw-Newton et al., 2002; Poff and Hart, 2002; Stanley and Doyle, 2003; Petts and Gurnell, 2005). For example, dam removals can restore connectivity of sediment in fluvial systems, both in the longitudinal direction downstream and the lateral direction between channel and floodplains (Kondolf et al., 2006). To determine the costs and benefits of repairing or removing a dam, specific predictions of channel response to dam removal and changes in connectivity are important to dam owners and agencies that oversee dam safety, waterway engineering, and riparian habitats. However, to date, predicting the locations of erosion and sedimentation has been elusive in these transient systems (Draut and Ritchie, 2015), especially when local and watershed scale constraints play a role (Major et al., 2012).

Beyond the management imperatives, dam removals merit investigation to improve our basic understanding of river processes. Dam removals present compelling natural-scale experiments on rivers—the dramatic increase in water surface slope due to lowering of the local base level creates a disturbance at a known place where the influence of slope on sediment transport and channel evolution can be tested. It is well established that water surface slope is a fundamental parameter in sediment transport and that a threshold for particle motion must be exceeded for a stream channel to erode (e.g. Shields, 1936; Meyer-Peter and Müller, 1948; Ferguson, 2012). Yet the interplay of temporal and spatial changes in slope and sediment transport and

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deposition is poorly understood in transient systems adjusting to disturbance. In particular, few studies have highlighted the importance of downstream spatial gradients in sediment transport in controlling the spatial pattern of erosion and deposition in recently disturbed fluvial systems (Paola and Voller, 2005; Bizzi and Lerner, 2013).

In the current predominant conceptual model, channel response to dam removal begins with the upstream migration of a knickpoint (e.g. Womack and Schumm, 1977), resulting in channel incision through reservoir sediments followed by channel widening (Simon, 1989; Doyle et al., 2002; Pizzuto, 2002; Pizzuto and O'Neal, 2009; Major et al., 2012). The steepness and height of the knickpoint front attenuates as it migrates upstream in the absence of resistant bedrock or other constraining features. Thus the greatest channel changes are expected generally to occur at dam proximal locations where the steep water slopes result in the greatest increases in shear stress (Williams, 1977; Doyle et al., 2002). This knickpoint migration and channel evolution conceptual model is most applicable to transitional channels forming in approximately homogenous material, a situation that can arise when relatively deep or wide reservoirs with pronounced sedimentation are drained.

However, dams and their impoundments occupy a variety of geomorphic settings, and this variability in settings cautions against expecting a similar response at every dam removal (Graf, 1999; Poff and Hart, 2002). Two recent dam removal studies highlight that reservoir response to dam removal is a) related to the width of the reservoir relative to the upstream channel (Sawaske and Freyberg, 2012) and b) influenced by local boundary conditions, such as bedrock outcrops (Pearson et al., 2011; Major et al., 2012). Here, we contend that narrow, shallow reservoirs tend to have thin deposits from sedimentation due to reduced accommodation space compared to deep, wide reservoirs. As these narrow reservoirs are drained, the variable integrity of the emerging bed and banks is likely to influence the spatial distribution of resistance to erosion and thus the spatial distribution of changes in slope and erosion potential within the drained reservoir. In such conditions, the geomorphic response to the disturbance of a dam removal may be highly controlled by boundary conditions, namely the spatial variability in resistance to erosion and erosive forces.

The purpose of this research is to test conceptual models of geomorphic response to dam removal in low gradient settings where contemporary (e.g., upstream flow regulation, urbanization) and pre-historical (locally thin alluvial cover over resistant bedrock) boundary conditions exist. We use the findings from the recent removal of the Homestead Dam and draining of its relatively narrow reservoir on the Ashuelot River in southeastern New Hampshire to test the prediction that downstream changes in erosive factors, such as bed resistance and spatial gradients in sediment transport, dictate the channel bed and bank response. Predicted and observed responses are documented through a combination of field surveys, innovative aerial lidar analysis, and one-dimensional hydrodynamic modeling. We characterize conditions before dam removal, use these conditions to predict locations of ensuing erosion and deposition, and monitor conditions for 15 months post removal. We document a channel response that deviates from the knickpoint migration and channel evolution conceptual model in significant ways because boundary conditions in the narrow, shallow reservoir impose variability on water surface slope in the drained reservoir.

We investigate the locations of erosion and deposition as a function of downstream changes in sediment transport and thresholds for sediment transport, which are modeled and predicted using information from the pre-removal surveys. Our analysis provides a framework for understanding the wide variety of river responses to dam removals and, more broadly, in transient systems.

2. Spatial patterns in sediment transport, erosion and deposition

Building on the Exner equation, which states that changes in stream bed elevation are a function of the negative divergence of sediment flux (Exner, 1920, 1925; Paola and Voller, 2005), it follows that, in the absence of significant tributary inputs, erosion should occur in reaches where sediment flux increases in the longitudinal direction. Conversely, aggradation should occur where sediment discharge decreases in the downstream direction. A necessary condition for either erosion or deposition is that flows are sufficient to mobilize sediment, which occurs when the Shields parameter, θ, exceeds a critical threshold for bed material entrainment, θ_{crit}, either at a location of erosion or upstream of a location of deposition. This concept can be expressed as follows:

$$\text{Given } \theta > \theta_{crit}$$
$$\text{If } \frac{dQ_s}{dx} > 0, \quad \text{then erosional}$$
$$\text{If } \frac{dQ_s}{dx} < 0, \quad \text{then depositional}$$

where Q_s is volumetric sediment discharge across the entire river width (in units volume per time in this study, but also could be expressed as mass per time), and x is distance downstream.

We use the dam removal as a natural experiment to predict two potential outcomes: (a) reaches of increasing downstream sediment transport are prone to erosion, and (b) reaches of decreasing downstream sediment transport are prone to deposition. A combination of aerial lidar, ground surveys, and HEC-RAS modeling are used to determine Q_s in a design storm and compare zones of predicted and observed erosion and deposition.

3. Site description

The Homestead Dam was an approximately 200 year old, 4 m high, 50 m wide, failing timber and rock crib structure located on the Ashuelot River in West Swanzey, New Hampshire that provided water storage for a now-defunct woolen mill (Figs. 1 and 2). It was a run-of-river dam lacking flow regulation. The ~9.5 km long reservoir behind

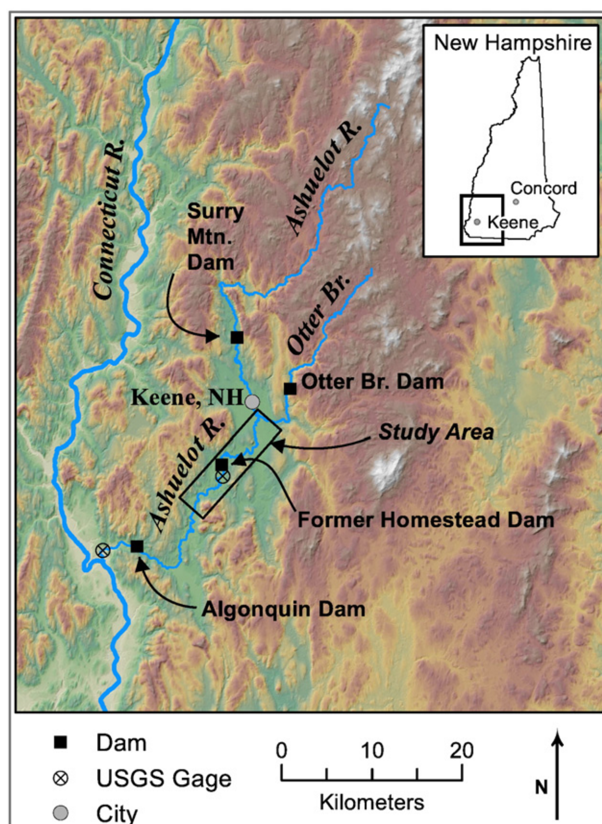

Fig. 1. Ashuelot River, showing the study reach and related dams.