Geomorphology 252 (2016) 158–170

Contents lists available at ScienceDirect

Geomorphology

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

Immediate changes in stream channel geomorphology, aquatic habitat, and fish assemblages following dam removal in a small upland catchment

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ARTICLE INFO

Article history:
Received 2 October 2014
Received in revised form 14 July 2015
Accepted 16 July 2015
Available online 17 July 2015

Keywords:
Dam removal
River restoration
Channel recovery
Fish habitat
Fragmentation

ABSTRACT

Dam removal is becoming an increasingly important component of river restoration, with >1100 dams having been removed nationwide over the past three decades. Despite this recent progression of removals, the lack of pre- to post-removal monitoring and assessment limits our understanding of the magnitude, rate, and sequence of geomorphic and/or ecological recovery to dam removal. Taking advantage of the November 2012 removal of an old (~190 year-old) 6-m high, run-of-river industrial dam on Amethyst Brook (26 km^2) in central Massachusetts, we identify the immediate eco-geomorphic responses to removal. To capture the geomorphic responses to dam removal, we collected baseline data at multiple scales, both upstream (~300 m) and downstream (>750 m) of the dam, including monumented cross sections, detailed channel-bed longitudinal profiles, embeddedness surveys, and channel-bed grain size measurements, which were repeated during the summer of 2013. These geomorphic assessments were combined with detailed quantitative electrofishing surveys of stream fish richness and abundance above and below the dam site and throughout the watershed and visual surveys of native anadromous sea lamprey (*Petromyzon marinus*) nest sites. Post-removal assessments were complicated by two events: (1) upstream knickpoint migration exhumed an older (ca. late eighteenth century) intact wooden crib dam ~120 m upstream of the former stone dam, and (2) the occurrence of a 10–20 year RI flood 6 months after removal that caused further upstream incision and downstream aggradation. Now that the downstream reach has been reconnected to upstream sediment supply, the predominant geomorphic response was bed aggradation and associated fining (30–60% reduction). At dam proximal locations, aggradation ranged from 0.3 to >1 m where a large woody debris jam enhanced aggradation. Although less pronounced, distal locations still showed aggradation with a mean depth of deposition of ~0.20 m over the 750-m downstream reach. Post-removal, but pre-flood, bed surveys indicate ~2 m of incision had migrated 25 m upstream of the former reservoir before encountering the exhumed dam, which now acts as the new grade control, limiting progressive headcutting. Approximately 1000 m^3 of sediment was evacuated in the first year, with ~67% of the volume occurring by pre-flood, process-driven (e.g., changes in base level) controls. The combination of changes in channel-bed sedimentology, the occurrence of a large magnitude flood, and the emergence of the new crib dam that is a likely barrier to fish movement was associated with major reductions in abundance and richness in sites downstream and immediately upstream adjacent to the former dam in post-removal sampling. At the same time, we documented the presence of four species of fish, including sea lamprey, which were not present above the dam prior to removal, indicating that upstream passage has been achieved; and we also documented lamprey spawning activity at sites immediately below the dam, which had previously been unsuitable owing to an excessively coarse and armored riverbed. Our results point to the importance of interactions between dam removal and flood disturbance effects, with important implications for short- and long-term monitoring and assessment of dam impacts to river systems.

1. Introduction

Driven in part by the increasing number of aging dams needing pending repair and also by broader societal goals, dam removal is progressively becoming part of river manager's toolkit for river restoration

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http://dx.doi.org/10.1016/j.geomorph.2015.07.027

(Shuman, 1995; Hart et al., 2002; Doyle et al., 2008; Doyle and Havlick, 2009; O'Connor et al., 2015). This national effort has led to the removal of over 1100 dams in the past several decades, averaging, at present, ~50 removed dams per year (Service, 2011). Because dam removal can minimize habitat fragmentation and reconnect riparian zones to fundamental hydrologic processes and channel-floodplain exchanges (Bednarek, 2001; Hart et al., 2002), many ecologists and environmental advocates embrace dam removal as a crucial element of river restoration. Recently, however, the scientific community has voiced some reluctance for indiscriminate endorsement of dam removal. Some scientists are concerned about the effect of released sediment on downstream geomorphic and ecological processes (Doyle et al., 2000, 2002, 2003; Grant, 2001; Pizzuto, 2002; Stanley and Doyle, 2003; Gangloff, 2013), especially as many of these previously stored sediments may be contaminated with pesticides, herbicides, and other byproducts of industrialization and mining such as mercury. The double-edged sword of ecological restoration associated with dam removal very much, thus, orbits around the geomorphic and biological impacts of sediment releases, including volume, flux, and sediment characteristics (size, sorting, etc.).

Research on dam removals has not kept pace with the currently brisk rate of removals. Despite the large number of removals over the past decades, there have been relatively few geomorphic or ecological assessments, especially detailed long-term monitoring or those linking the geomorphic adjustments specifically to the ecological (cf. Stanley et al., 2002; Stanley and Doyle, 2003; Pollard and Reed, 2004; East et al., 2015; Warrick et al., 2015). In an extensive compilation of dam removals in the U.S. and abroad, a recent USGS study (Bellmore et al., 2015) indicates that only ~130 dam removals have had any monitoring of any kind, with most lacking post-removal comparative assessments. The minimal documentation results in part from the frequent politicization and extended permitting process often limiting extensive pre-removal baseline data. Post-removal assessments are also commonly plagued by limited monitoring funds to document ecological and geomorphic recovery. Because of these limitations, dam removal research has evolved gradually from an initial phase that dealt with the conceptualization of potential impacts (Bednarek, 2001; Hart et al., 2002; Pizzuto, 2002; Poff and Hart, 2002; Shafroth et al., 2002; Stanley and Doyle, 2003) to progressively more field-based analyses of late that capture actual effects (Doyle et al., 2003, 2005; Cheng and Granata, 2007; Burroughs et al., 2009; Kibler et al., 2011; Pearson et al., 2011; Major et al., 2012; Draut and Ritchie, 2013; East et al., 2015; Harris and Evans, 2014; Magirl et al., 2015; Wilcox et al., 2014; Gartner et al., 2015; Randle et al., 2015; Warrick et al., 2015).

These case studies have documented specific changes in channel morphology and associated longitudinal effects, but no universal process-based model has been developed nor have these studies converged on universal responses. They have, though, documented the type and variability of responses and the fundamental importance of a spatial perspective in understanding the specific changes in fluvial systems following dam removal. The exact response depends on several factors including the volume, caliber, and cohesion of sediment stored in the reservoir; flow frequency; downstream channel dimensions (Pizzuto, 2002; Graf, 2003; Major et al., 2008; Sawaske and Freyberg, 2012; Bountry et al., 2013; MacBroom and Schiff, 2013); as well as dam function, size, and physiographic location (Poff and Hart, 2002; Graf, 2006). Some studies demonstrate a significant increase in sediment transport downstream (Burroughs et al., 2009), while other locations have little or no change in sediment transport downstream of the dam (Cheng and Granata, 2007). Downstream of a removed dam, bed sediment caliber typically initially decreases resulting from the release of finer sediments from the reservoir, which then increases in successive storms (Wohl and Cenderelli, 2000; Cheng and Granata, 2007; Pearson et al., 2011). Sediment routing downstream of the dam is also variable, with some streams exhibiting translation of a sediment wave and others an attenuated dispersive wave that gradually erodes (Wohl and Cenderelli, 2000; Doyle et al., 2002; Pizzuto, 2002).

These sedimentological effects are further complicated in the context of large flow events. Extreme flows acting immediately after a dam has been removed, when the channel is highly vulnerable to rapid and extreme adjustment (owing to the major change in hydraulic control) sets up the possibility for interactive effects on channels and river habitats that are difficult to anticipate. Recent research (Pearson et al., 2011; Major et al., 2012; Grant and Lewis, 2015) suggests that even in the absence of post-removal large flows, upward of 50% of the initial reservoir sediment volume can be evacuated within the first year—a conceptual model initially posited by Pizzuto (2002) where he distinguished between process-based erosion (e.g., knickpoint migration) and event-based erosion (e.g., large floods).

The ecological effects of dam removals are similarly complex, affecting different ecosystem components at a range of temporal and spatial scales (Stanley and Doyle, 2003). For stream fish populations and assemblages, barrier removal can result in rapid colonization of previously unoccupied upstream areas (Pess et al., 2014). This rapid upstream movement has often been observed, particularly with highly mobile diadromous species such as migratory salmonids (Pess et al., 2014). The role of barriers and barrier removal on the distribution and diversity of stream resident fishes has been less well appreciated, but several studies indicate that barriers to movement are associated with reduced richness and abundance (Nislow et al., 2011; Diebel et al., 2014). In addition to direct effects of reconnection and upstream access, dams and dam removal may also have a strong influence on physical habitat. Effects on habitat are driven in large part by the geomorphic processes described previously. As many of these processes are associated with large flows that occur infrequently, effects on habitat may not be fully manifest until years or decades following dam removal. However, in those cases where extreme flows occur in close association with dam removal, significant immediate change may occur given the potential for geomorphic instability and readjustment. In turn, these rapid adjustments may have indirect (via changes in habitat) and direct (via event-associated mortality) on populations and assemblages. Further, while large, high-profile dam removals have been well studied and monitored, we have considerably less information on the effects of removing small run-of-river dams in small upland catchments (Csiki and Rhoads, 2010). These structures are numerous and ubiquitous within the heavily-settled northeastern and north-central U.S. and are a major target of dam removal efforts.

Despite the recent spate of dam removal research, several important questions remain about the timing and spatial extent of geomorphic responses and the rate at which ecosystems respond to these transient adjustments. Dam removals, in many ways, are perhaps the closest analog in geomorphology to a controlled natural experiment: they represent the removal of a disturbance fixed in time and space with extant boundary and initial conditions. Therefore, rather than considering each dam removal as a unique case study, we suggest each dam removal represents an important boundary condition of reservoir sediment properties, dam removal style ('blow-n-go' vs. staged removal), dam trapping efficiency, valley confinement, and channel gradient. Using the staged removal of a 6-m-high, run-of-river dam that impounded a high gradient, coarse gravel-bedded stream, we elucidate the type, magnitude, and spatial variability of geomorphic adjustments immediately following its removal and further document the associated ecological responses. Thus, we have three major geomorphic research questions: (i) how does grain size change downstream of the former impoundment as the upstream to downstream sediment flux gets reestablished; (ii) what are the channel adjustments (bed elevation, planform, etc.) associated with the change in sediment flux; and (iii) what is the length scale of these geomorphic adjustments? Ecologically, our major questions are: (i) how does fish demography change following dam removal; (ii) how do changes in bed sediment composition enhance or diminish bed spawning habitat requirements; and (iii) are fish able to colonize new upstream territory now made available by dam removal?