Geomorphology 246 (2015) 687–708

Contents lists available at ScienceDirect

Geomorphology

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

Reprint of: Large-scale dam removal on the Elwha River, Washington, USA: River channel and floodplain geomorphic change☆

Amy E. East [a,*], George R. Pess [b], Jennifer A. Bountry [c], Christopher S. Magirl [d], Andrew C. Ritchie [e], Joshua B. Logan [a], Timothy J. Randle [c], Mark C. Mastin [d], Justin T. Minear [f], Jeffrey J. Duda [g], Martin C. Liermann [b], Michael L. McHenry [h], Timothy J. Beechie [b], Patrick B. Shafroth [i]

[a] U.S. Geological Survey, Pacific Coastal and Marine Science Center, 400 Natural Bridges Drive, Santa Cruz, CA 95060, USA
[b] National Marine Fisheries Service, National Oceanic and Atmospheric Administration, Seattle, WA 98112, USA
[c] U.S. Bureau of Reclamation, P.O. Box 25007, Mail Code 86-68240, Denver, CO 80225, USA
[d] U.S. Geological Survey, Washington Water Science Center, 934 Broadway, Suite 300, Tacoma, WA 94802, USA
[e] National Park Service, Olympic National Park, 600 E. Park Avenue, Port Angeles, WA 98362, USA
[f] U.S. Geological Survey, California Water Science Center, 6000 J Street, Placer Hall, Sacramento, CA 95819, USA
[g] U.S. Geological Survey, Western Fisheries Research Center, 6505 NE 65[th] St., Seattle, WA 98115, USA
[h] Lower Elwha Klallam Tribe, 51 Hatchery Rd., Port Angeles, WA 98363, USA
[i] U.S. Geological Survey, Fort Collins Science Center, 2150 Centre Ave., Bldg. C, Fort Collins, CO 80526, USA

ARTICLE INFO

Available online 6 May 2015

Keywords:
Fluvial geomorphology
Dams
Dam removal
Channel evolution
Floodplain
Sediment wave

ABSTRACT

A substantial increase in fluvial sediment supply relative to transport capacity causes complex, large-magnitude changes in river and floodplain morphology downstream. Although sedimentary and geomorphic responses to sediment pulses are a fundamental part of landscape evolution, few opportunities exist to quantify those processes over field scales. We investigated the downstream effects of sediment released during the largest dam removal in history, on the Elwha River, Washington, USA, by measuring changes in riverbed elevation and topography, bed sediment grain size, and channel planform as two dams were removed in stages over two years.

As 10.5 million t (7.1 million m^3) of sediment was released from two former reservoirs, downstream dispersion of a sediment wave caused widespread bed aggradation of ~1 m (greater where pools filled), changed the river from pool–riffle to braided morphology, and decreased the slope of the lowermost river. The newly deposited sediment, which was finer than most of the pre-dam-removal bed, formed new bars (largely pebble, granule, and sand material), prompting aggradational channel avulsion that increased the channel braiding index by almost 50%. As a result of mainstem bed aggradation, floodplain channels received flow and accumulated new sediment even during low to moderate flow conditions. The river system showed a two- to tenfold greater geomorphic response to dam removal (in terms of bed elevation change magnitude) than it had to a 40-year flood event four years before dam removal. Two years after dam removal began, as the river had started to incise through deposits of the initial sediment wave, ~1.2 million t of new sediment (~10% of the amount released from the two reservoirs) was stored along 18 river km of the mainstem channel and 25 km of floodplain channels. The Elwha River thus was able to transport most of the released sediment to the river mouth. The geomorphic alterations and changing bed sediment grain size along the Elwha River have important ecological implications, affecting aquatic habitat structure, benthic fauna, salmonid fish spawning and rearing potential, and riparian vegetation. The response of the river to dam removal represents a unique opportunity to observe and quantify fundamental geomorphic processes associated with a massive sediment influx, and also provides important lessons for future river-restoration endeavors.

Published by Elsevier B.V.

1. Introduction

Many fundamental, long-standing problems in earth-surface-process research involve the need to understand how landscapes respond to changing sediment supply (Gilbert, 1917; Antevs, 1952; Eschner et al., 1983; James, 1989; Benda and Dunne, 1997; Ashworth et al., 2004; Cowie et al., 2008; Covault et al., 2013). Well-controlled laboratory and flume investigations provide valuable steps toward

☆ A publisher's error resulted in this article appearing in the wrong issue. The article is reprinted here for the reader's convenience. For citation purposes, please use the original publication details; Geomorphology, 228 (2015), pp. 765–786.
DOI of original article: http://dx.doi.org/10.1016/j.geomorph.2014.08.028.

* Corresponding author. Tel.: +1 831 460 7533.
E-mail address: aeast@usgs.gov (A.E. East).

http://dx.doi.org/10.1016/j.geomorph.2015.04.027
0169-555X/Published by Elsevier B.V.

understanding how sediment-supply pulses affect processes such as stream-channel evolution, bar formation, and avulsion (e.g., Lisle et al., 1997; Braudrick et al., 2009; Madej et al., 2009; Tal and Paola, 2010; Pryor et al., 2011); and modeling studies allow simulated manipulation of landscapes over a range of scales (e.g., Cui and Parker, 2005; Jerolmack and Paola, 2007; Karssenberg and Bridge, 2008; Wang et al., 2011). However, opportunities to study landscape response to major sediment influx over large field scales are much rarer and usually are not anticipated in advance (e.g., dam failure, volcanic eruptions, landslides, or debris flows; Meyer and Martinson, 1989; Montgomery et al., 1999; Hoffman and Gabet, 2007; Casalbore et al., 2011; Gran, 2012; Guthrie et al., 2012; Pierson and Major, 2014; Tullos and Wang, 2014). Therefore, landscape adjustment to a substantial sediment-supply increase remains seldom quantified in the field. In this study we analyze river channel and floodplain response to a uniquely large and anticipated sediment pulse resulting from the largest dam removal globally, on the Elwha River, Washington, USA (Fig. 1).

Conveyance of a large-scale sediment slug, or wave, down a gravel-bed river can evolve through dispersion and translation (Nicholas et al., 1995; Lisle et al., 1997, 2001). Grain size distribution of the wave, grain size relative to the extant bed, sediment-pulse volume, river discharge, slope, and channel width all influence the speed and evolution of the sediment wave (Lisle et al., 1997, 2001; Cui et al., 2003a, b; Cui and Parker, 2005; Lisle, 2008; Sklar et al., 2009). In steep mountain rivers with Froude numbers greater than about 0.4, sediment waves tend to be dispersive with little translational behavior (Lisle et al., 1997, 2001; Cui and Parker, 2005; Lisle, 2008), though some translation in mountain river settings has been documented if the pulse grain size is smaller than the preexisting bed, has a narrow grain size distribution, and has a low height-to-length ratio (Pitlick, 1993; Wohl and Cenderelli, 2000; Sklar et al., 2009). For large sediment pulses released (i.e., eroded and transported) during dam removal projects, Pizzuto (2002) posited that dispersion with little translation would dominate sediment wave dynamics, but dispersion and translation together have been documented for dam removal projects with smaller sediment releases (Simons and Simons, 1991; Doyle et al., 2002; Stanley et al., 2002; Tullos et al., 2010).

Sediment wave dynamics along a river system have important implications for geomorphic evolution. For example, alluvial sections of gravel-bed rivers subject to increased bedload and aggradation

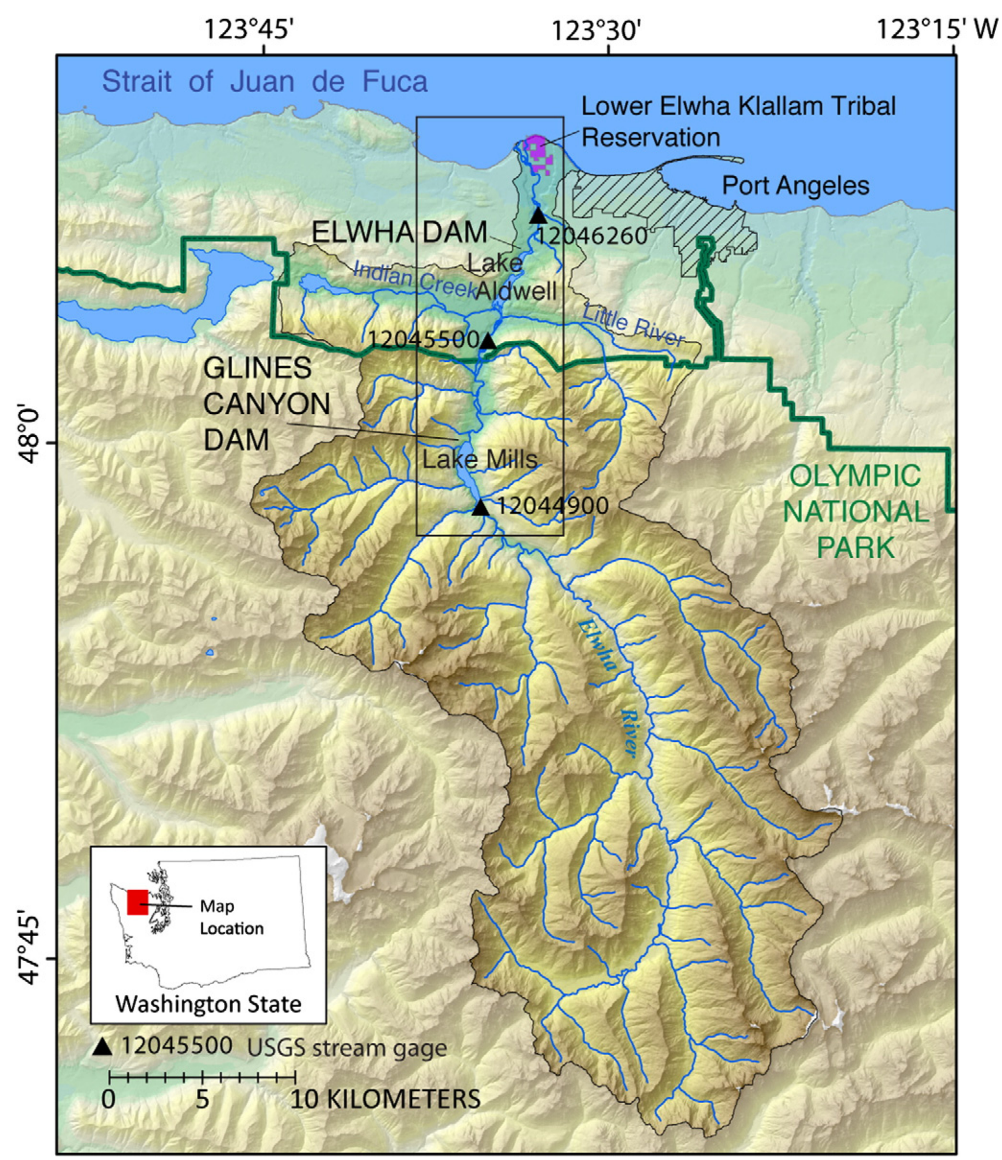

Fig. 1. Elwha River watershed and surroundings, Washington, USA. The Elwha River 'middle reach' extends from Glines Canyon Dam site to the upstream end of former Lake Aldwell; the Elwha River 'lower reach' extends from Elwha Dam site to the river mouth. Box shows location of map in Fig. 3A.