Erosion of reservoir sediment from the removal of two large dams on the Elwha river, Washington, USA

L'érosion des sédiments de réservoir suite aux démantèlements de deux grands barrages sur la rivière Elwha, état de Washington, États-Unis

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RÉSUMÉ

Les démantèlements simultanés des barrages Elwha et Glines Canyon sur la rivière Elwha dans l'état de Washington aux États-Unis (opération la plus importante de démantèlement de barrage de l'histoire) ont entraîné une baisse du niveau de base des réservoirs. Ce démantèlement a déclenché une succession d'étapes d'évolution de la rivière, avec une dégradation, une érosion latérale des berges, et une redéposition des sédiments qui ont considérablement modifié le paysage du réservoir.

Le niveau du lac Aldwell derrière le barrage Elwha, d'une hauteur de 32 m, a été abaissé par étapes entre juin 2011 et mai 2012. Le niveau du lac Mills derrière le barrage Glines Canyon d'une hauteur de 64 m, a été abaissé entre octobre 2010 et août 2014. Les deux premières années de ces projets ont provoqué le transport en aval de 23% des sédiments du lac Aldwell (1,12 ± 0,07 millions de m^3), et de 37% de ceux du lac Mills (5,95 ± 0,12 millions de m^3), un volume équivalent à quatre décennies de sédiments transportés depuis l'amont. Le paysage du réservoir présente aujourd'hui une série de terrasses sédimentaires de différentes hauteurs composées de sédiments grossiers couvrant ses dépôts plus fins.

ABSTRACT

The concurrent removal of Elwha Dam and Glines Canyon Dam on the Elwha River in Washington, USA (largest dam removal in history) resulted in the base-level lowering of the reservoirs. Dam removal triggered a series of channel evolution steps: degradation, lateral terrace bank erosion, and redeposition that dramatically altered the reservoir landscape.

Lake Aldwell, behind the 32-m high Elwha Dam, was incrementally lowered between June 2011 and May 2012. Lake Mills, behind the 64-m high Glines Canyon Dam, was incrementally lowered between October 2010 and August 2014. The first two years of dam removal resulted in the erosion and downstream release of 23% of the sediment in Lake Aldwell (1.12 ± 0.07 million m^3) and 37% of the sediment in Lake Mills (5.95 ± 0.12 million m^3), representing nearly four decades of sediment supply from the upstream watershed. The reservoir landscape now consists of a series of sediment terraces of varying heights composed of prograded coarse sediment overlying fine lakebed deposits.

KEYWORDS

Channel evolution, delta, reservoir sediment erosion

1 INTRODUCTION

Conceptual models predicting the geomorphic response of reservoir sediment deposits to dam removal have been developed (Cannatelli and Curran, 2012) based on relatively small dams (<10 m) with sediment volumes that were less than the decadal sediment load of the river. In the only recent example of a large sediment volume associated with a dam removal, a hole in the bottom of the 100-year old, 38-m high Condit Dam on the White Salmon River, Washington, USA was blasted on October 26, 2011 (Wilcox et al., 2014). The reservoir was rapidly drained and more than 60% of the estimated 1.8 million m^3 of sediment was released within the first 15 weeks after the blast (Wilcox et al., 2014).

Removal of the Elwha and Glines Canyon Dams on the Elwha River near Port Angeles, Washington, USA provided a unique opportunity to investigate the effects of two concurrent, phased dam removals on erosion, redistribution, and release of the largest sediment volume associated with any dam removal (Randle et al., 2014). Nearly a century of coarse sediment supply (sand, gravel, and cobble) was trapped in the reservoir deltas. The delta and lakebed sediment deposits consisted of both cohesive and non-cohesive layers, providing an opportunity to investigate how cohesion influences erosion following dam removal.

The Elwha River flows north about 72 km from the Olympic Mountains to the Strait of Juan de Fuca, about 10 km west of Port Angeles. Most of the watershed (83% of 833 km^2) is within the boundaries of Olympic National Park. Average annual precipitation ranges from 1 m at the river mouth to 6 m on Mount Olympus. The average annual discharge is 42 m^3/s and the 2-year flood peak is 400 m^3/s. The natural river bed is composed of gravel, cobbles, boulders, and sand, with some exposed bedrock.

2 METHODS

Data collection included river discharge, reservoir and dam crest elevations, time-lapse imagery, water-surface elevation recorders, terrestrial and bathymetric surveys, structure-from-motion (SfM)-based photogrammetry, aerial and terrestrial light detection and ranging (LiDAR) surveys, sediment grain size analyses, and field observations. Analyses included measurements of vertical channel incision, lateral erosion, down-valley progradation of the reservoir deltas, and deposition of reservoir sediments (Randle et al., 2014).

3 RESULTS AND DISCUSSION

The reservoir sediment response to the phased and concurrent drawdown of two reservoirs on the Elwha River, Washington, USA during dam removal was investigated by measuring changes in reservoir topography and channel morphology as a function of base level lowering, river discharge, and cohesion.

Reservoir drawdown increments of 3 to 5 m were sufficient to initiate channel degradation and delta progradation across the entire width of the receding reservoir, which redistributed decades of delta sediment throughout the reservoir while the lake still remained (Randle et al., 2014). The first year of dam removal resulted in up to 5 m of incision through the Lake Aldwell delta down to the predam surface, and just over 20 m of incision through the Lake Mills delta. Downstream progradation of the delta resulted in a few meters of deposition in Lake Aldwell and 2 to 10 m in Lake Mills on top of prodelta and lakebed sediments. A braided channel developed and widened up to tenfold across the entire width of the reservoir. The most extensive lateral erosion occurred in coarse, non-cohesive sediment during multi-week hold periods coinciding with flows between the mean annual flow and the 2-year flood peak. Channel widening in the more cohesive fine sediments (clay and silt) of the prodelta and lakebed was less than half of that in the coarse, non-cohesive delta sediments. Dam removal resulted in the erosion and downstream release of 23% of the sediment in Lake Aldwell (1.12 ± 0.07 million m^3) and 37% of the sediment in Lake Mills (5.95 ± 0.12 million m^3), equivalent to nearly four decades of sediment supply from the upstream watershed within a two-year period. A significant portion of the reservoir sediment is expected to remain as sediment terraces within the reservoir landscape, but additional erosion is expected during future floods until the river reaches quasi-equilibrium.

After phased dam removal, the reservoir landscape consists of a series of sediment terraces of varying heights composed of prograded coarse sediment overlying fine lakebed deposits (Fig. 1 and 2) (Randle et al., 2014). The predam surface is exposed along the river corridor, and abundant 1 to 3 m stumps from pre-removal forests create unique morphology where the river interacts with the predam landscape.

Figure 1. Photograph looking upstream along the former Lake Aldwell delta.

Figure 2. Photograph looking downstream along the former Lake Mills toward Glines Canyon Dam site.

4 CONCLUSION

The removal of Elwha and Glines Canyon Dams on the Elwha River, Washington provided a unique opportunity to investigate reservoir sediment erosion and channel evolution in response to tens of meters of base-level lowering from phased dam removal. The phased dam removal effectively controlled the rate and extent of reservoir sediment erosion and downstream release. Despite relatively low clay content, the cohesive properties of fine sediments limited lateral erosion in the wide reservoirs to one-third to one-half of the later erosion in coarse, non-cohesive sediment.

Results from the Elwha River dam removals are consistent with conceptual models and other studies which find that reservoir sediment erosion and channel evolution are influenced by the hydraulic height of the dam, rate and style of dam removal, sediment management strategies, deposit thickness, impounded sediment volume relative to mean annual load, deposit and reservoir geometry, grain size and degree of cohesion, and hydrology.

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