

# **Sediment Monitoring during Elwha River Dam Removals: Lessons Learned during the Nation's Largest Dam Removal Project**

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The gradual, staged removal of two large dams on the Elwha River located on the Olympic Peninsula, Washington, USA, was the largest dam removal project in U.S. history when it began in September 2011. For almost 100 years, the 32-m tall Elwha Dam, located on the Elwha River 8 km upstream from the river mouth at the Strait of Juan de Fuca, blocked access of anadromous salmonids to the upper watershed. The construction in 1927 of a second dam (64-m tall Glines Canyon Dam located 22 km upstream from the river mouth) further restricted the river and trapped fluvial sediment sourced from the upper watershed. Beginning in September 2011, the incremental removal of both dams resulted in the release of large volumes of sediment that had profound effects on the downstream morphology of the river and posed challenges for scientists tasked with monitoring the transport of sediment. While some changes such as large-scale aggradation of the river bed and the subsequent incision of channel deposits were expected and planned for, other factors such as the timing, magnitude and characteristics of sediment transport were largely unknown. Before dam removals and throughout the duration of the project, a network of U.S. Geological Survey (USGS) streamgages located upstream and downstream of both dams on the Elwha River provided real-time hydrologic information such as stage, discharge and turbidity to managers, engineers and scientists planning for and studying the effects of dam removal. These telemetered data were vital to implementing an adaptive management program used to direct the rate and extent of dam removal to ensure mitigation services such as water treatment operations and levee protection did not exceed design criteria. A bedload impact-plate system installed and operated by the U. S. Bureau of Reclamation (USBR) at the downstream gage location was instrumented with geophones and accelerometers for monitoring coarse bedload ( $\geq 16\text{mm}$ ) transport rates (Hildale et al. 2015). Physical sediment samples, both suspended and bedload, were collected periodically and opportunistically during the project and were the basis for sediment-surrogate relations used to calculate daily sediment loads. Despite modest runoff during the first three years following the start of dam removal (peak discharges were below the 2-year flood), annual total sediment load in year 2 (7.1 Mt) was the largest of the 5-year study whereas the largest daily suspended-sediment load occurred in year 5 (430 kt) coincident with the timing of the 9.4-year flood discharge (Ritchie et al. 2018a). During the 5 years following initiation of dam removal, a total sediment flux of 18.9 Mt (~65% of trapped reservoir sediment) was recorded at the downstream gage, of which 24 percent was estimated as bedload (Ritchie et al. 2018b).

In the summer of 2011, prior to the beginning of dam removal, nephelometric turbidimeters and pressure transducers for measuring stage were installed at two USGS gages on the Elwha River; one located upstream of both dams (12044900), and one located downstream of both dams (12046260) (Figure 1). A long-term USGS gage (12045500) with more than 100 years of discharge record and located between the former reservoirs (middle gage) was operated throughout the study and recorded river stage using an in-stream pressure transducer until significant channel aggradation required transitioning to a non-contact radar stage sensor.



**Figure 1.** Elwha River basin prior to the start of dam removals in September 2011, showing the locations of the former Elwha Dam which formed Lake Aldwell and the former Glines Canyon Dam which formed Lake Mills.

At the downstream gage (12046260), an optical backscatter turbidimeter was used to measure exceptionally high turbidity levels beyond the operable range of the nephelometric turbidimeter. Other sediment surrogate technologies used at the downstream gage included a side-looking acoustic Doppler velocimeter (1500 kHz) deployed during the first two years of sediment monitoring, and an acoustic point sensor (LISST-ABS) set near (within 2-m) both turbidity sensors and deployed in 2016. Suspended-sediment concentration (SSC) samples were collected periodically from a pedestrian bridge 350 m downstream from the downstream gage over a

range of discharge and turbidity conditions using standard USGS cross-section sampling methods (Edwards and Glysson 1999). An automated point sampler was used to collect daily composite SSC samples during year 2 of the study and was deployed periodically thereafter for event-based and seasonal sampling. Using the SSC samples, sediment-surrogate regressions were developed using established techniques (Rasmussen et al. 2009; Landers et al. 2016) and suspended-sediment loads were determined at the downstream gage as a product of SSC and discharge from the long-term gage (12045500) adjusted for time of travel and flow contributions from the ungagged reach (Magirl et al. 2015). The bedload impact-plate system at the downstream gage measured the frequency of particle-plate collisions (impulses) from which correlations with physical sample data were developed to estimate the sediment flux of particles  $\geq 16$  mm (Hilldale et al. 2015). Due to the cost and complexity of sampling bedload near (within 10-m) the impact-plate system, bedload was sampled much less frequently than SSC although samples were successfully collected during multiple years and at various discharges (Hilldale et al. 2015). Standard USGS stream gaging methods, requiring the collection of continuous stage data and discrete discharge measurements (Rantz 1982), provided the basis for a stage-discharge residual analysis (Anderson and Konrad 2019) at the middle gage (12045500) and was used for assessing the passage of a large sediment wave generated during removal of the Glines Canyon Dam.

Turbidity was the single-most utilized surrogate for continuously monitoring the large range of observed SSC following dam removals. A combination of turbidimeters, one each for low/high SSC conditions, proved reliable surrogates for SSC within their operable ranges. During the 5-year study, the nephelometric turbidimeter measured a range of 0.1 – >1,500 formazin nephelometric units (FNU), although values >1,300 FNU were not used due to accuracy concerns. By comparison, the optical backscatter turbidimeter measured from 2.6 – 3,400 formazin backscatter units (FBU), and values <100 FBU were not used due to accuracy concerns. In combination, the turbidimeters monitored an SSC range of 0.1-21,400 mg/L as determined from log-transformed turbidity-SSC regressions developed for each sensor. Telemetered 15-minute turbidity data provided the additional benefits of informing fisheries managers with water-quality conditions for the successful reintroduction of salmonids and was used by downstream water treatment facilities for maintaining functionality during periods of high sediment loads. Because turbidity was measured at the upstream and downstream gages with identical sensors and consistent calibration protocols (Wagner et al. 2006), direct comparisons between upstream and downstream measurements were possible in assessing progress toward background conditions following dam removals.

As a parameter, river stage provided multiple uses during and long after the 3-year dam removal process. Stage measured at USGS gages provided real-time flood warning for the safe removal of dam structures and the protection of the human population in the downstream floodplain. The stage record at the long-term USGS gage (12045500) was used not only for determination of discharge but also as a proxy for monitoring the aggradation/incision of the channel bed and the detection and tracking of a large-scale dispersive sand wave initiated following the breach of the upstream Glines Canyon Dam (East et al. 2018; Ritchie et al. 2018b). Stage-discharge record at the upstream-most USGS gage (12044900), in combination with pre-dam removal studies (e.g., Curran et al. 2009) provided estimates of background sediment load needed for closure of the

basin-wide sediment budget. When combined with physical bedload samples, impulse-frequency measurements from geophones embedded within bedload impact-plates provided empirical estimates of sediment flux for particles  $\geq 2$  mm. The combination of suspended-sediment and bedload monitoring allowed valuable comparisons with volumetric change measurements made in complimentary studies to validate how much sediment had evacuated the reservoir and reached the river mouth. Being able to document when 90% of released sediment reached the river mouth was important for assessing the finality of downstream sediment impacts from dam removal.

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