Prepared in cooperation with the National Park Service

# Estimates of Sediment Load Prior to Dam Removal in the Elwha River, Clallam County, Washington

Scientific Investigations Report 2009–5221

U.S. Department of the Interior
U.S. Geological Survey

**Cover:** Logjam on the Elwha River (looking upstream) entering Lake Mills, Clallam County, Washington. (Photograph taken by Christopher P. Konrad, U.S. Geological Survey, 2004.)

# Estimates of Sediment Load Prior to Dam Removal in the Elwha River, Clallam County, Washington

By Christopher A. Curran, Christopher P. Konrad, Johnna L. Higgins, and
Mark K. Bryant

Prepared in cooperation with the National Park Service

Scientific Investigations Report 2009–5221

**U.S. Department of the Interior**
**U.S. Geological Survey**

**U.S. Department of the Interior**
KEN SALAZAR, Secretary

**U.S. Geological Survey**
Suzette M. Kimball, Acting Director

U.S. Geological Survey, Reston, Virginia: 2009

For more information on the USGS—the Federal source for science about the Earth, its natural and living resources, natural hazards, and the environment, visit http://www.usgs.gov or call 1-888-ASK-USGS

For an overview of USGS information products, including maps, imagery, and publications, visit http://www.usgs.gov/pubprod

To order this and other USGS information products, visit http://store.usgs.gov



Suggested citation:
Curran, C.A.., Konrad, C.P., Higgins, J.L., and Bryant, M.K., 2009, Estimates of sediment load prior to dam removal in the Elwha River, Clallam County, Washington: U.S. Geological Survey Scientific Investigations Report 2009–5221, 18 p.

# Contents

## Figures



## Tables

# Conversion Factors, Datums, and Acronyms and Abbreviations

## Conversion Factors

| Multiply | By | To obtain |
|---|---|---|
| | Length | |
| centimeter (cm) | 0.3937 | inch (in.) |
| millimeter (mm) | 0.03937 | inch (in.) |
| meter (m) | 3.281 | foot (ft) |
| kilometer (km) | 0.6214 | mile (mi) |
| | Area | |
| square kilometer ($km^2$) | 247.1 | acre |
| square kilometer ($km^2$) | 0.3861 | square mile ($mi^2$) |
| | Volume | |
| cubic meter ($m^3$) | 1.308 | cubic yard ($yd^3$) |
| liter (L) | 0.2642 | gallon (gal) |
| milliliter (mL) | 0.03382 | ounce, fluid (fl. oz) |
| | Flow rate | |
| cubic meter per second ($m^3/s$) | 35.31 | cubic foot per second ($ft^3/s$) |
| | Mass | |
| gram (g) | 0.03527 | ounce, avoirdupois (oz) |
| megagram (Mg) | 1.102 | ton, short (2,000 lb) |
| megagram per day (Mg/d) | 1.102 | ton per day (ton/d) |
| megagram per year (Mg/yr) | 1.102 | ton per year (ton/year) |
| megagram per square kilometer ($Mg/km^2$) | 2.8547 | ton per square mile ($ton/mi^2$) |
| milligram (mg) | $3.527 \times 10^{-5}$ | ounce, avoirdupois (oz) |

Concentrations of chemical constituents in water are given in milligrams per liter (mg/L).

## Datums

Vertical coordinate information is referenced to the North American Vertical Datum of 1988 (NAVD 88).

Horizontal coordinate information is referenced to the North American Datum of 1983 (NAD 83).

Altitude, as used in this report, refers to distance above the vertical datum.

## Acronyms and Abbreviations

| | |
|---|---|
| EDI | equal discharge increment |
| GCLAS | Graphical Constituent Loading Analysis Software |
| OLS | ordinary least-squares |
| NWIS | National Water Information System |
| RK | river kilometer |
| USGS | U.S. Geological Survey |

This page intentionally left blank.

# Estimates of Sediment Load Prior to Dam Removal in the Elwha River, Clallam County, Washington

By Christopher A. Curran, Christopher P. Konrad, Johnna L. Higgins, and Mark K. Bryant

## Abstract

Years after the removal of the two dams on the Elwha River, the geomorphology and habitat of the lower river will be substantially influenced by the sediment load of the free-flowing river. To estimate the suspended-sediment load prior to removal of the dams, the U.S. Geological Survey collected suspended-sediment samples during water years 2006 and 2007 at streamflow-gaging stations on the Elwha River upstream of Lake Mills and downstream of Glines Canyon Dam at McDonald Bridge. At the gaging station upstream of Lake Mills, discrete samples of suspended sediment were collected over a range of streamflows including a large peak in November 2006 when suspended-sediment concentrations exceeded 7,000 milligrams per liter, the highest concentrations recorded on the river. Based on field measurements in this study and from previous years, regression equations were developed for estimating suspended-sediment and bedload discharge as a function of streamflow. Using a flow duration approach, the average total annual sediment load at the gaging station upstream of Lake Mills was estimated at 327,000 megagrams with a range of uncertainty of +57 to -34 percent (217,000–513,000 megagrams) at the 95 percent confidence level; 77 percent of the total was suspended-sediment load and 23 percent was bedload. At the McDonald Bridge gaging station, daily suspended-sediment samples were obtained using an automated pump sampler, and concentrations were combined with the record of streamflow to calculate daily, monthly, and annual suspended-sediment loads. In water year 2006, an annual suspended-sediment load of 49,300 megagrams was determined at the gaging station at McDonald Bridge, and a load of 186,000 megagrams was determined upstream at the gaging station upstream of Lake Mills. In water year 2007, the suspended-sediment load was 75,200 megagrams at McDonald Bridge and 233,000 megagrams upstream of Lake Mills. The large difference between suspended-sediment loads at both gaging stations shows the extent of sediment trapping by Lake Mills, and a trap efficiency of 0.86 was determined for the reservoir. Pre-dam-removal estimates of suspended-sediment load and sediment-discharge relations will help planners monitor geomorphic and habitat changes in the river as it reaches a dynamic equilibrium following the removal of dams.

## Introduction

The two dams on the Elwha River in Clallam County, Washington (fig. 1) are scheduled for removal in the near future: the Elwha Dam at river kilometer (RK) 7.9, which forms Lake Aldwell, and the Glines Canyon Dam at RK 21.6, which forms Lake Mills. Both dams were constructed early in the 20th century without provision for fish passage and largely are responsible for the loss of anadromous fish runs, which historically occurred throughout the year. In 1992, restoration of the river was mandated by Congress under the Elwha River Ecosystem and Fisheries Restoration Act (Public Law 102-495). By 1995, the Secretary of the Interior decided that removal of both dams was a necessary step toward river restoration (U.S. Department of the Interior, 1995). Because most of the Elwha River basin is within the Olympic National Park, the National Park Service, the primary Federal agency responsible for the preservation and protection of this land, was tasked with removing the dams to allow the full restoration of native anadromous fisheries and the broader Elwha River ecosystem.

Since their construction, both dams have accumulated sediment that otherwise would have been transported downstream. The volume of retained sediment has been estimated at about 10.6 million cubic meters in Lake Mills and 3.1 million cubic meters in Lake Aldwell (Childers and others, 1999).The removal of both dams on the Elwha River will be one of the largest dam removal projects ever attempted and the release of stored sediment by the free-flowing river will result in profound changes to the channel morphology and habitat of the lower river. In cooperation with the National Park Service, the U.S. Geological Survey (USGS) made pre-dam-removal measurements of suspended-sediment load during water years 2006 and 2007. This information will provide a baseline of suspended-sediment data useful to planners and scientists monitoring geomorphic and habitat changes in the river as it reaches a dynamic equilibrium after the dams are removed.

## Description of Study Area

The Elwha River is about 70 km long and its headwaters are in the central part of the Olympic Mountains at an altitude of about 1,350 m. The river flows from the mountains generally northward, passes through the two dams, crosses a coastal terrace and discharges into the Strait of Juan de Fuca (fig. 1), the waterway that connects Puget Sound with the Pacific Ocean.

As is characteristic of rivers on the Olympic Peninsula, the Elwha River is fed seasonally by varying contributions from snowmelt, groundwater discharge, and precipitation runoff. Eighty-three percent of the Elwha River basin is within the Olympic National Park and includes 830 $km^2$ of mostly forested land with many areas of pristine wilderness. Most of the basin is within the eastern core of the Olympic Mountains where accreted marine sediments in the form of sandstone and shale formations predominate (Tabor and Cady, 1978). The climate in the Elwha River basin is maritime with relatively wet, mild winters and dry, cool summers. Annual precipitation in the basin ranges from about 560 cm at the upper elevations to about 140 cm near the mouth of the river (Munn and others, 1998).

## Purpose and Scope

This report provides suspended-sediment concentrations measured during water years 2006 and 2007 (October 1, 2005–September 30, 2007) at two USGS gaging stations on the Elwha River: Elwha River above Lake Mills (station no. 12044900) upstream of Elwha and Glines Canyon dams, and Elwha River at McDonald Bridge (station no. 12045500) between the dams. Data for suspended-sediment and bedload measurements made by the USGS during water years 1995–98 at the gaging station upstream of Lake Mills also are included. Using all available data at this station, regression models were developed for estimating suspended-sediment discharge and bedload discharge as a function of streamflow. These models were used to estimate monthly and annual sediment loads. At the McDonald Bridge gaging station, daily suspended-sediment concentrations from pumped samples were combined with the record of streamflow to calculate daily, monthly, and annual suspended-sediment loads. The difference in loads upstream and downstream of Lake Mills was used to compute the trap efficiency of the reservoir. Collectively, these measurements of suspended-sediment provide a baseline for monitoring change in sediment transport following dam removal.

# Methods of Data Collection and Analysis

During water years 2006 and 2007, suspended-sediment samples were collected from the river over a range of flows either as depth-integrated samples, grab samples, or pumped samples. Depth-integrated samples were collected across the river channel using the Equal Discharge Increment (EDI) method as outlined by Edwards and Glysson (1999). Grab samples were collected at the edge of the river when conditions did not allow for safe depth-integrated measurements. Pumped samples were collected with an automated pump sampler installed on the downstream right bank at the McDonald Bridge gaging station (12045500). For all methods of collection, water samples were analyzed to determine suspended-sediment concentration, reported in milligrams per liter and, when possible, the percent mass of sediment greater than 0.0625 mm in size was reported as the sand fraction. All suspended-sediment sample analyses were performed by the USGS Cascades Volcano Observatory sediment laboratory in Vancouver, Washington.

Both USGS gaging stations in the Elwha River basin provided a record of streamflow during the 2006–07 study. Real-time and historical streamflow information for the gaging stations Elwha River above Lake Mills (12044900), and Elwha River at McDonald Bridge (12045500) are available from the USGS National Water Information System website (http://waterdata.usgs.gov/wa/nwis).

## Elwha River above Lake Mills (12044900)

The gaging station upstream of Lake Mills is installed in a bedrock-confined reach 400 m upstream of Lake Mills and 4.3 km upstream of the Glines Canyon Dam at RK 25.7 (fig. 1). The gage measures streamflow that drains an area covering 513 $km^2$ or 62 percent of the total area of the Elwha River basin. Because this gaging station is upstream of both dams, streamflow and sediment data measured at the site are representative of the natural flow regime and provide an important reference for comparison with data collected in the altered reaches downstream of the dams. A daily record of streamflow at this gaging station is available from March 1994 through May 1998, and from February 2004 through September 2008. In 2004, a motorized bank-operated cableway was installed and used for measuring streamflow and collecting suspended-sediment samples (fig. 2).

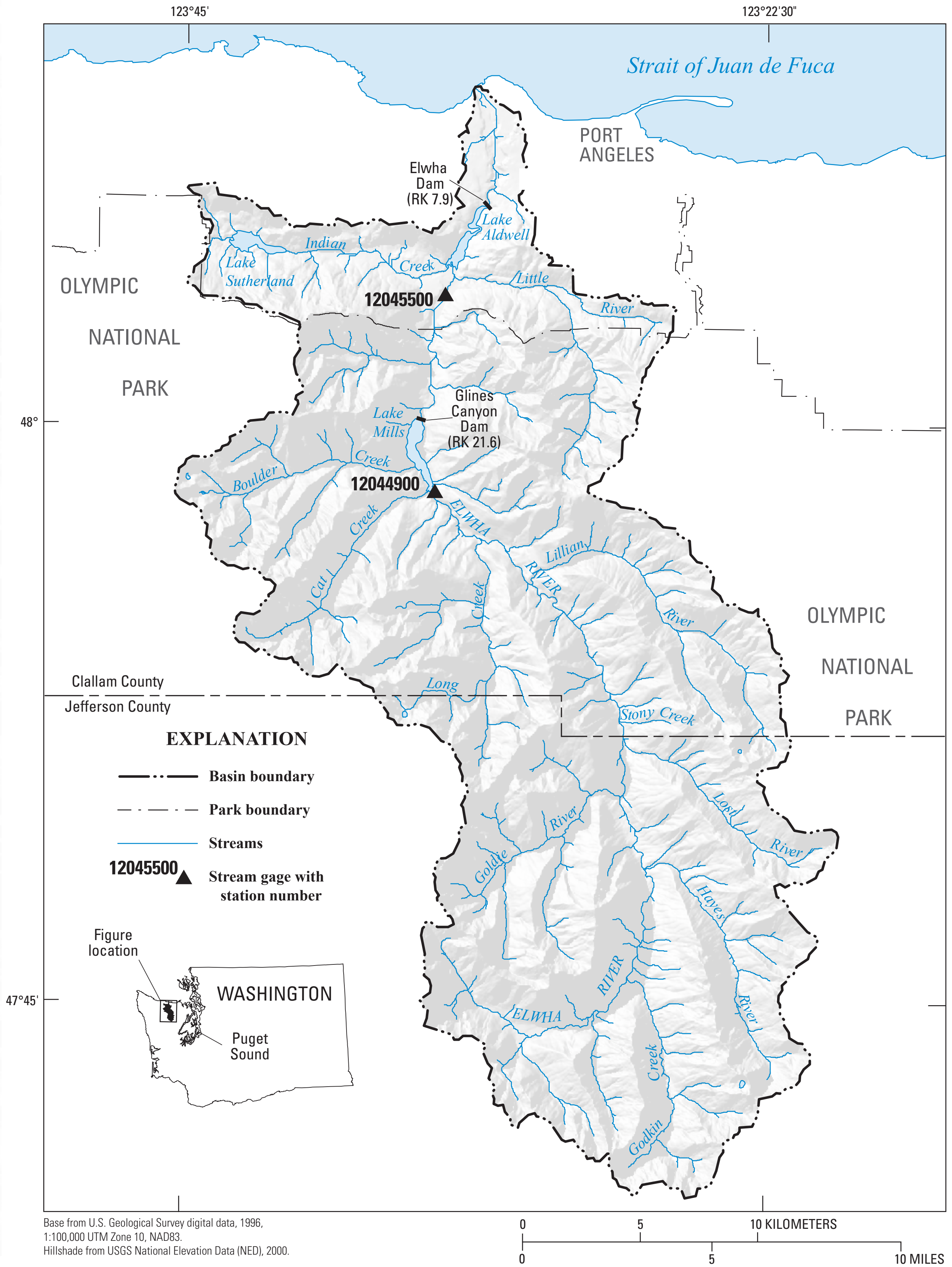


**Figure 1.** Study area and U.S. Geological Survey gaging stations where sediment samples were collected, water years 1995–98, and 2006–07, Elwha River basin, Clallam County, Washington. (RK, river kilometer.)

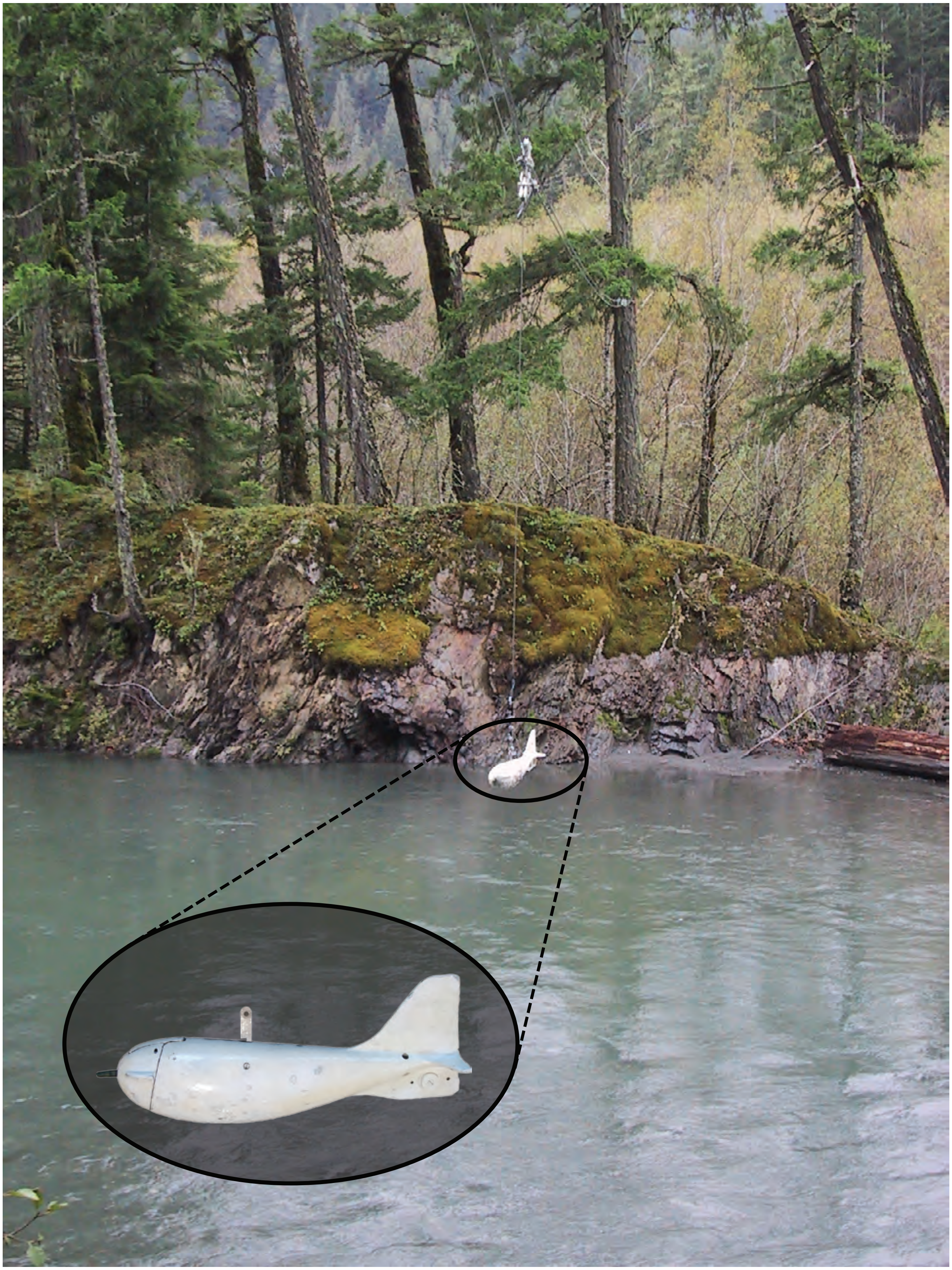

**Figure 2.** Bank-operated cableway system and D-74 suspended-sediment sampler viewed from the U.S. Geological Survey gaging station Elwha River above Lake Mills (12044900), Elwha River basin, Clallam County, Washington. Photograph taken by Christopher P. Konrad, U.S. Geological Survey, 2006.

## Suspended-Sediment Sample Collection

During water years 2006 and 2007, the EDI method was used to collect depth-integrated suspended-sediment samples along a cross section, with sample locations determined by a preceding measurement of streamflow. Depth-integrated samples were collected using a D-74 suspended-sediment sampler and pint-sized glass bottles in accordance with USGS sediment data-collection protocol (Edwards and Glysson, 1999). Measurements of suspended-sediment concentration were made over a range of flows throughout the study period and the data were used with previous measurements to develop a regression model expressing the relation between suspended-sediment concentration and streamflow.

Measurements of suspended-sediment concentration were made during water years 1995–98 at the gaging station upstream of Lake Mills and used the Equal Width Increment (EWI) method to collect depth-integrated samples (Edwards and Glysson, 1999). These measurements subsequently were used with samples collected from an automated pump sampler at this site to calculate daily, monthly, and annual suspended-sediment loads for water years 1995–97 (Wiggins and others, 1995, 1996, and 1997).

## Regression Analysis

For the regression model, concentration and discharge values were transformed to base-10 logarithmic values, and an ordinary least-squares (OLS) regression was computed. Re-expressing estimates from a log-regression equation into original units can result in a low bias (Helsel and Hirsch, 1992), so a correction factor determined from the mean of the re-transformed residuals expressed in original units was applied to all estimates of suspended-sediment concentration. The resulting regression model expressed as a power equation and corrected for bias takes the form:

$$C_S = c_f \times a \times Q^b , \qquad (1)$$

where

$C_S$ is the suspended-sediment concentration in milligrams per liter;

$c_f$ is the bias correction factor;

*a* and *b* are the coefficients determined from the regression analysis; and

$Q$ is streamflow in cubic meters per second (Bragg and others, 2007).

The regression model was used to determine hourly estimates of suspended-sediment concentration based on the corresponding hourly streamflow record of the gaging station. These hourly estimates of suspended-sediment concentration then were used in the Graphical Constituent Loading Analysis Software (GCLAS; Koltun and others, 2006) with the continuous record of streamflow at the gaging station to estimate monthly and annual sediment loads.

## Bedload Sample Collection

Bedload is defined as fluvial sediment that moves by sliding, rolling, or bouncing along on the streambed (Edwards and Glysson, 1999). Following the Lake Mills drawdown study in 1994 (Childers and others, 1999), the USGS continued to collect bedload measurements in anticipation of the imminent removal of the Glines Canyon and Elwha Dams. From November 1994 to October 1997, measurements were made over a range of flows using the EWI method.

Measurements of bedload discharge were made using the sampling device, the “Elwha sampler,” that was designed and used for the Lake Mills drawdown study (Childers and others, 1999). The Elwha sampler has a 10.2 × 20.3-cm intake nozzle with an expansion ratio of 1.40. The sampler generally was used from a boat, although a modified hand-held version was used at low flows when the channel could be waded. To obtain a bedload sample, the sampler was placed on the channel bed for a specified period, usually 30 seconds with the intake facing upstream. After 30 seconds, the sampler was raised and emptied of sediment. Thirteen bedload samples generally were collected at evenly spaced stations along the cross section. Samples collected at each cross section were composited prior to analysis. All bedload samples were analyzed for dry weight and grain-size distribution by the USGS Cascades Volcano Observatory sediment laboratory in Vancouver, Washington.

Bedload discharges were calculated from the measurements using this equation:

$$Q_B = (K \times W_T \times M_T)(t_T \times N_w) , \qquad (2)$$

where

$Q_B$ is the bedload discharge in megagrams per day;

$K$ is a unit conversion factor equal to 0.0864;

$W_T$ is the total width of the stream cross-section in meters;

$M_T$ is the total mass of sample collected in the cross-section in grams;

$t_T$ is the total time the sampler was on the bed in seconds; and

$N_w$ is the sampler width in meters (Edwards and Glysson, 1999).

## Elwha River at McDonald Bridge (12045500)

The gaging station at McDonald Bridge, at RK 13.9, is installed in a bedrock-confined reach 1.7 km upstream of Lake Aldwell and 7.7 km downstream of the Glines Canyon Dam at RK 13.9 (fig. 3). The gage measures streamflow that drains an area covering 697 $km^2$ or 84 percent of the total area of the Elwha River basin. The gaging station has a streamflow record that spans more than a century, from October 1897 to December 1901 and from October 1918 to the present (2007). The Glines Canyon Dam is operated by the Bureau of Reclamation as "run-of-the-river," a water-management strategy that attempts to minimize regulation and maintain natural flows (Kevin Yancy, Bureau of Reclamation, written commun., 2007).

An automatic pump sampler was installed at this gaging station and operated from October to July, the primary months of sediment transport, during water years 2006 and 2007. The automatic sampler collected daily water samples by pumping water from an intake that extended into the river. The sampling frequency was adjusted to 4-hour intervals during a single large flood event on November 6–7, 2006. Because samples collected with a pump sampler may not have been representative of the entire cross section, samples also were collected manually from the cableway using the EDI sampling method. Depth-integrated samples were collected along the cross section using a D-74 suspended-sediment sampler with pint-sized glass bottles. Sediment concentrations determined from the manually-collected samples were used to correct any bias associated with the location of the intake of the automatic pump sampler. Daily, monthly, and annual suspended-sediment loads were calculated using GCLAS based on the continuous record of streamflow and sediment concentrations determined from the automatic pump sampler and manual sampling methods.

**Figure 3.** Elwha River looking downstream of U.S. Geological Survey gaging station Elwha River at McDonald Bridge (12045500), Elwha River basin, Clallam County, Washington. Photograph taken by Christopher P. Konrad, U.S. Geological Survey, 2006.

## Estimates of Sediment Load

Variability in the magnitude, timing, and frequency of streamflow can greatly influence the amount of sediment transport that occurs from year to year. In analyzing the results of sediment monitoring for any given year, the discharge conditions for that year should be considered relative to the historical record. The magnitude and timing of streamflow during the study period relative to the mean daily streamflow for the period of record at the Elwha River at McDonald Bridge gaging station is shown in figure 4. Similar to most mountain-fed rivers in the Pacific Northwest, most of the annual streamflow in the Elwha River usually occurs during winter, as a result of direct runoff from precipitation and during summer, as a result of melting snowpack. Compared to the long-term annual mean streamflow at the McDonald Bridge gaging station (42.8 $m^3/s$, based on the 92-year period of record), streamflow for water year 2006 was average (42.4 $m^3/s$), and for water year 2007 was 14 percent above average (48.7 $m^3/s$) (U.S. Geological Survey, 2008).

Peak river flows during the study period occurred as a result of “pineapple-express” events, a type of regional weather pattern characterized by unseasonably warm temperatures and intense rainfall. The largest of these peaks occurred in early November during water year 2007, 346 $m^3/s$ at the gaging station upstream of Lake Mills and 592 $m^3/s$ at the gaging station at McDonald Bridge (U.S. Geological Survey, 2008). By comparison, peak flows occurred in late December during water year 2006, 262 $m^3/s$ at the gaging station upstream of Lake Mills and 329 $m^3/s$ at the gaging station at McDonald Bridge (U.S. Geological Survey, 2008).

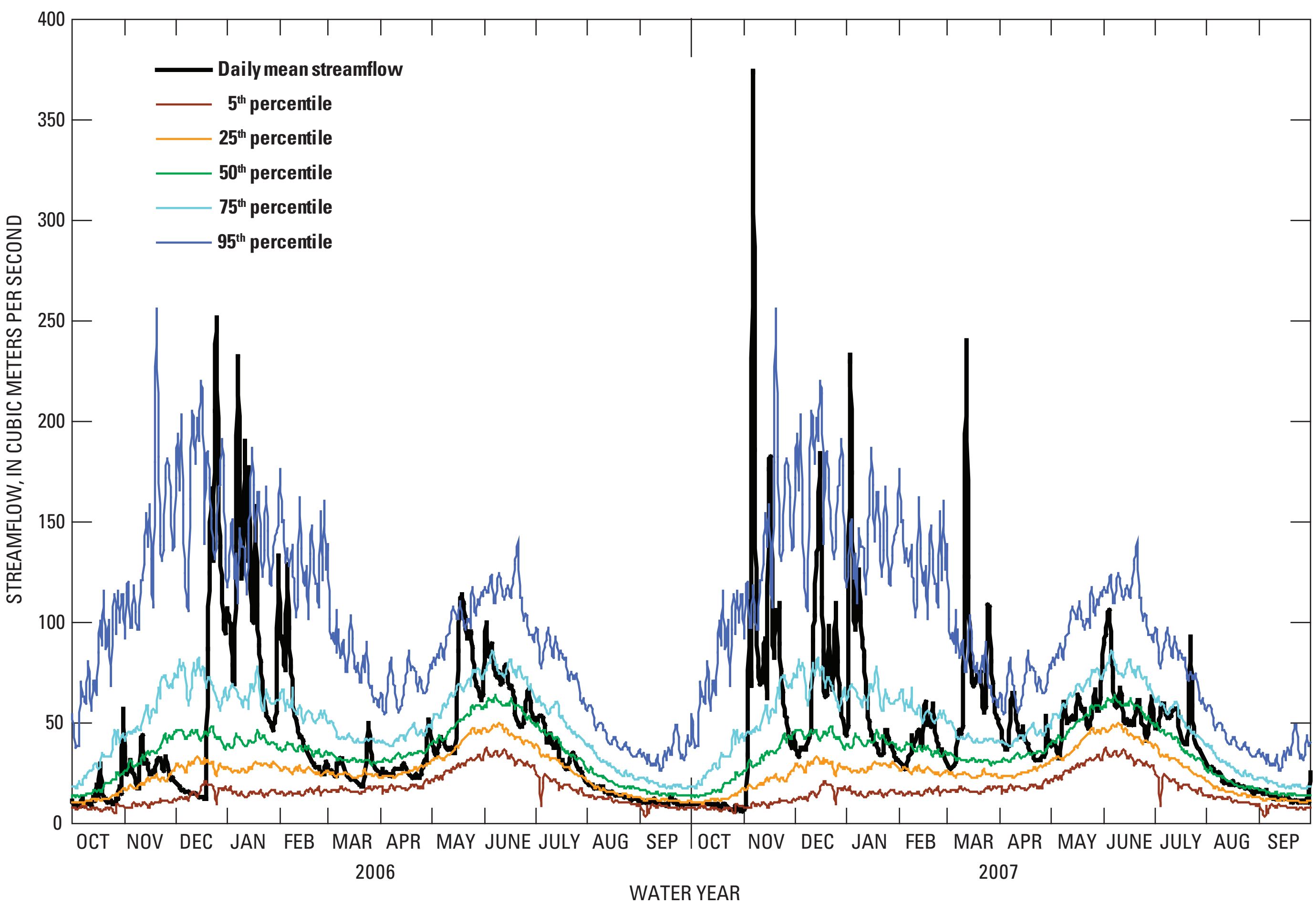


**Figure 4.** Daily mean streamflow and percentiles based on 92 years of record (1897–2005), Elwha River at McDonald Bridge (12045500), Clallam County, Washington, water years 2006 and 2007.

## Elwha River above Lake Mills (12044900)

Suspended-sediment data collected from the Elwha River at the gaging station upstream of Lake Mills during water years 2006–07 are summarized in table 1. Most samples were collected using the EDI method and samples with low suspended-sediment concentrations generally were composited in the laboratory prior to analysis. The highest suspended-sediment concentrations and river flows recorded during the study period occurred near the peak of a precipitation-driven flood on November 6, 2006, for which an instantaneous streamflow of 346 $m^3/s$ was recorded at 10:45 AM (Pacific Standard Time). Two sets of EDI measurements (10 samples) and 2 grab samples were collected near the peak of the flood. Suspended-sediment concentrations in these samples ranged from 5,703 to 7,325 mg/L and were higher than concentrations recorded during the 1994 drawdown study by Childers and others (1999). Suspended-sediment samples also were collected 3 days prior to the flood peak and ranged from 304 to 504 mg/L, and streamflow was about 85 $m^3/s$ (fig. 5).

The mass percentage of suspended sediment finer than 0.0625 mm was determined for all EDI samples collected before and during the flood peak. Results from this limited size analysis (fig. 5) indicate that the percentage of fine suspended sediment (that is, silts and clays) increased as the flood progressed. This increase in fine sediment load likely was due to the magnitude and timing of this precipitation-driven event, which was exceptionally large and the "first flush" of the river basin following a dry summer.

Because a continuous record of suspended-sediment concentration was not available at this site for 2006–07, a regression model was determined for suspended-sediment concentration and streamflow to estimate monthly and annual suspended-sediment loads. Concentration data from samples collected during water years 2006–07 (table 1) and data collected by the USGS at this site during water years 1995–98 (appendix A) were used with corresponding streamflow data to develop the regression model. During development of the model, it was observed that streamflow measurements less than 30 $m^3/s$ heavily influenced the coefficients of the regression line, yet the percentage of total suspended-sediment load contributed from streamflows less than 30 $m^3/s$ was minor (less than 0.5 percent). Because the regression line was unduly influenced by concentrations measured in this flow range, these measurements were trimmed from the data set and were not used in the model (fig. 6). This approach is consistent with the method of developing sediment-transport curves over specific flow regimes as outlined by Glysson (1987), except that a separate curve for low flows was not necessary for this analysis.

**Table 1.** Suspended-sediment and streamflow data from samples collected at Elwha River above Lake Mills (12044900), Elwha River basin, Clallam County, Washington, water years 2006 and 2007.

[**Streamflow**: Instantaneous streamflow recorded at the streamflow-gaging station at the time of sample collection. **Abbreviations**: $m^3/s$, cubic meter per second; mg/L, milligram per liter; mm, millimeter; <, less than; –, no data]

| Date | Time | Streamflow ($m^3/s$) | Suspended-sediment concentration (mg/L) | Percent fines (grain size <0.0625 mm) |
|---|---|---|---|---|
| 11-02-05 | 12:58 | 22.4 | 5 | – |
| 11-02-05 | 13:03 | 22.4 | 5 | – |
| 12-05-05 | 14:26 | 14.4 | 1 | – |
| 12-05-05 | 14:26 | 14.4 | 1 | – |
| [1]12-29-05 | 11:00 | 88.1 | 106 | – |
| 05-04-06 | 10:20 | 34.8 | 21 | – |
| 05-04-06 | 10:25 | 34.8 | 3 | – |
| 05-17-06 | 12:08 | 91.5 | 77 | 70 |
| 05-17-06 | 12:13 | 91.8 | 78 | 67 |
| 11-03-06 | 15:26 | 86.7 | 345 | 64 |
| 11-03-06 | 15:38 | 86.7 | 366 | 62 |
| 11-06-06 | 12:00 | 326 | 6,810 | 78 |
| 11-06-06 | 12:30 | 320 | 6,770 | 78 |

[1] Grab sample only.

To consider possible hysteresis, data points with concentrations greater than 50 mg/L were identified as having been measured on a rising or falling limb of a flood peak. However, no evidence for hysteresis was apparent due to the limited data set at the upper end of the flow regime.

The OLS regression equation, which includes a correction factor for bias associated with the log-transformation of variables, is expressed as:

$$C_S = cf_S \times 1.17 \times 10^{-4} \times Q_W^{\ 3.0}\,, \qquad (3)$$

where

$C_S$ is the suspended-sediment concentration in milligrams per liter;

$cf_S$ is the bias correction factor equal to 1.07; and

$Q_W$ is streamflow in cubic meters per second.

The coefficient of determination ($R^2$) for the regression equation is 0.92.

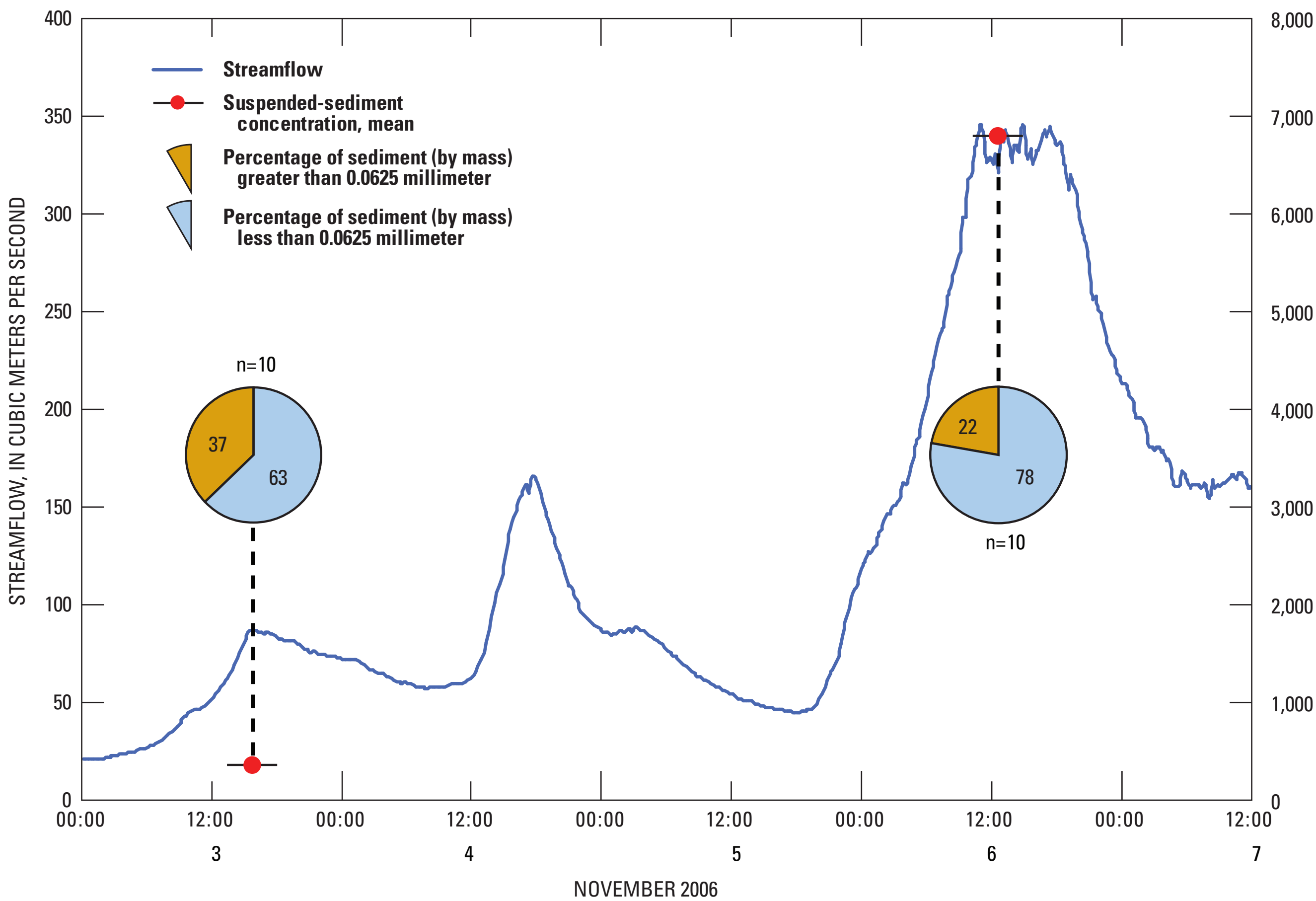


**Figure 5.** Streamflow, mean suspended-sediment concentrations of equal discharge increment (EDI), and percentage of fine sediment by mass, November 3 and 6, 2006 Elwha River above Lake Mills (12044900), Clallam County, Washington.

The regression model (equation 3) and the continuous streamflow record at the gaging station were used with GCLAS to estimate monthly and annual suspended-sediment loads (appendix B). The annual suspended-sediment load at the gaging station upstream of Lake Mills was estimated at 186,000 and 233,000 Mg for water years 2006 and 2007, respectively.

To quantify the uncertainty in the regression model, the 95 percent confidence intervals for prediction and the mean were computed. The confidence interval for prediction is the likely range of suspended-sediment concentrations for a single measurement made at a particular streamflow, whereas the confidence interval for the mean is the likely range of concentrations for the mean of a set of independent measurements made at a particular streamflow (Helsel and Hirsch, 1992).

## Suspended-Sediment Discharge

The rate of suspended-sediment discharge in a river can be calculated from the product of the mean suspended-sediment concentration and the streamflow (Guy, 1970). The regression model developed for determining suspended-sediment concentration as a function of streamflow, equation 3, was modified to calculate suspended-sediment discharge as follows:

$$Q_S = 1.25 \times 10^{-4} \times Q_W{}^{4.0} \times K, \qquad (4)$$

where

$Q_S$ is the suspended-sediment discharge in megagrams per day;

$Q_W$ is streamflow in cubic meters per second; and

$K$ is a unit conversion factor equal to 0.0864.

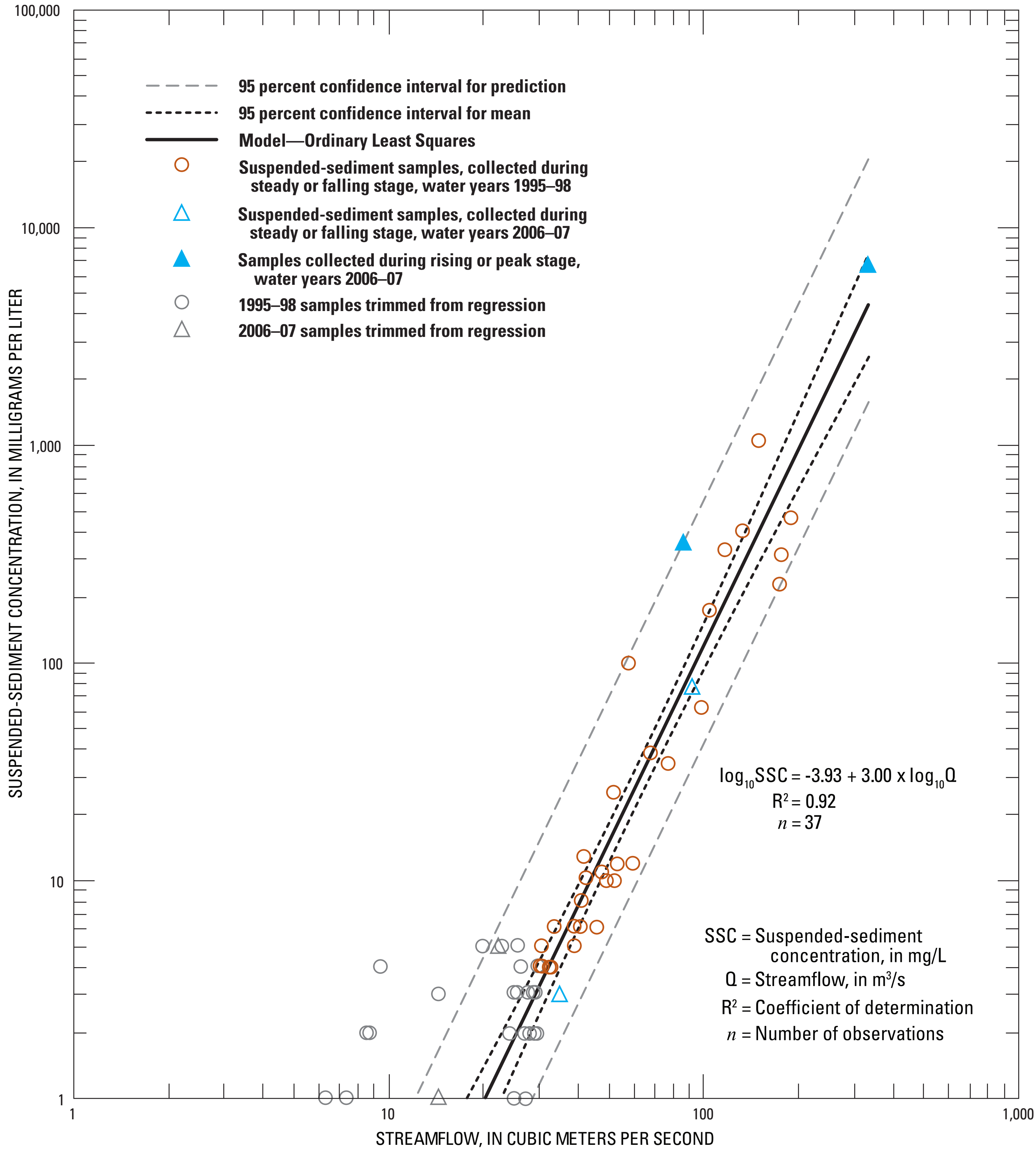


**Figure 6.** Regression model used to estimate suspended-sediment concentration from streamflow, Elwha River above Lake Mills (12044900), Clallam County, Washington, water years 1995–98 and 2006–07.

## Bedload Discharge

During water years 1995–98, 25 bedload measurements were made on the Elwha River at the gaging station upstream of Lake Mills (appendix C). Bedload discharge for each cross section measured was calculated using equation 2. During the 1994 Lake Mills drawdown study by Childers and others (1999), 19 measurements were made at this site and were included in this analysis. All measurements were matched with corresponding streamflows recorded at the gaging station and an OLS regression on log-transformed variables was used to describe a bedload transport curve relating bedload as a function of streamflow (fig. 7). The transport curve equation used for estimating bedload discharge is:

$$Q_B = cf_B \times 0.01 \times Q_W^{\,2.41}, \qquad (5)$$

where

$Q_B$ is the bedload discharge in megagrams per day;

$cf_B$ is the bias correction factor equal to 1.13; and

$Q_W$ is streamflow in cubic meters per second.

The $R^2$ for the linear-regression equation is 0.77.

The uncertainty in the bedload transport model for prediction and mean was determined at the 95 percent confidence level.

## Total Sediment Load Estimates

The regression models developed for suspended-sediment and bedload transport as a function of streamflow were used to estimate the total sediment load into Lake Mills. A flow-duration/sediment-rating curve approach as outlined by Julien (1998) was used to estimate total load. The flow-duration curve is a cumulative-frequency curve showing the percentage of time specific streamflows were equaled or exceeded (Searcy, 1959). A flow-duration curve based on 8 years of daily streamflow data (water years 1995–98 and 2005–08) obtained from the gaging station upstream of Lake Mills was developed using the Weibull plotting position formula as explained by Helsel and Hirsch (1992). The flow-duration curve was combined with the sediment transport equations for suspended sediment (equation 4) and bedload (equation 5) to determine an estimate of total annual sediment load (appendix D). Using this approach, the total load at the gaging station upstream of Lake Mills was estimated to be 327,000 Mg/yr with a range of uncertainty of +57 to -34 percent (217,000–513,000 Mg/yr) at the 95 percent confidence level. The percentage of suspended-sediment load was estimated at 77 percent (251,000 Mg/yr), and the percentage of annual bedload was estimated to be 23 percent (75,500 Mg/yr).

# Elwha River at McDonald Bridge (12045500)

An automated sampler was used to collect 451 pumped samples from the Elwha River at the gaging station at McDonald Bridge during water years 2006–07 and 16 EDI measurements were made in water year 2006 (table 2). The highest recorded suspended-sediment concentration at this site was 946 mg/L from a pumped sample during the pineapple express flood of November 6, 2006. The peak streamflow recorded during this flood was 592 $m^3/s$ at 12:45 PM. The flood was anticipated, and the sampling frequency of the pump sampler was increased to 4-hour intervals 3 days prior to the flood peak and continued throughout the peak and during the recession. During the course of the flood, the peak in suspended-sediment concentration lagged the streamflow peak by about 8 hours (fig. 8). Delayed sediment peaks of 2–3 days were measured in the reservoir drawdown study by Childers and others (1999) when streamflow was much lower than during the November 2006 flood event. During the November 2006 event, delayed sediment peaks were the result of slower sediment transport through the reservoir relative to the propagation of the flood peak.

**Table 2.** Suspended-sediment concentrations and streamflow from samples collected using the equal discharge increment method at Elwha River at McDonald Bridge (12045500), Elwha River basin, Clallam County, Washington.

[Samples analyzed at the Cascades Volcano Observatory, Vancouver, Washington. **Streamflow**: Instantaneous streamflow recorded at the streamflow-gaging station at the time of sample collection. **Abbreviations**: $m^3/s$, cubic meter per second; mg/L, milligram per liter]

| Date | Time | Streamflow ($m^3/s$) | Suspended-sediment concentration (mg/L) |
|---|---|---|---|
| 11-02-05 | 15:10 | 23.0 | 3 |
| 11-02-05 | 15:15 | 23.0 | 2 |
| 12-05-05 | 13:39 | 17.1 | 0 |
| 12-05-05 | 13:41 | 17.1 | 1 |
| 12-29-05 | 12:52 | 101 | 117 |
| 12-29-05 | 12:57 | 101 | 122 |
| 01-23-06 | 11:38 | 57.2 | 21 |
| 01-23-06 | 11:40 | 57.2 | 21 |
| 02-16-06 | 13:30 | 37.4 | 6 |
| 02-16-06 | 13:34 | 36.5 | 7 |
| 03-13-06 | 11:54 | 22.9 | 5 |
| 03-13-06 | 11:58 | 22.9 | 4 |
| 04-04-06 | 11:28 | 25.1 | 2 |
| 04-04-06 | 11:31 | 25.1 | 2 |
| 05-04-06 | 13:19 | 36.0 | 1 |
| 05-04-06 | 13:23 | 36.0 | 1 |

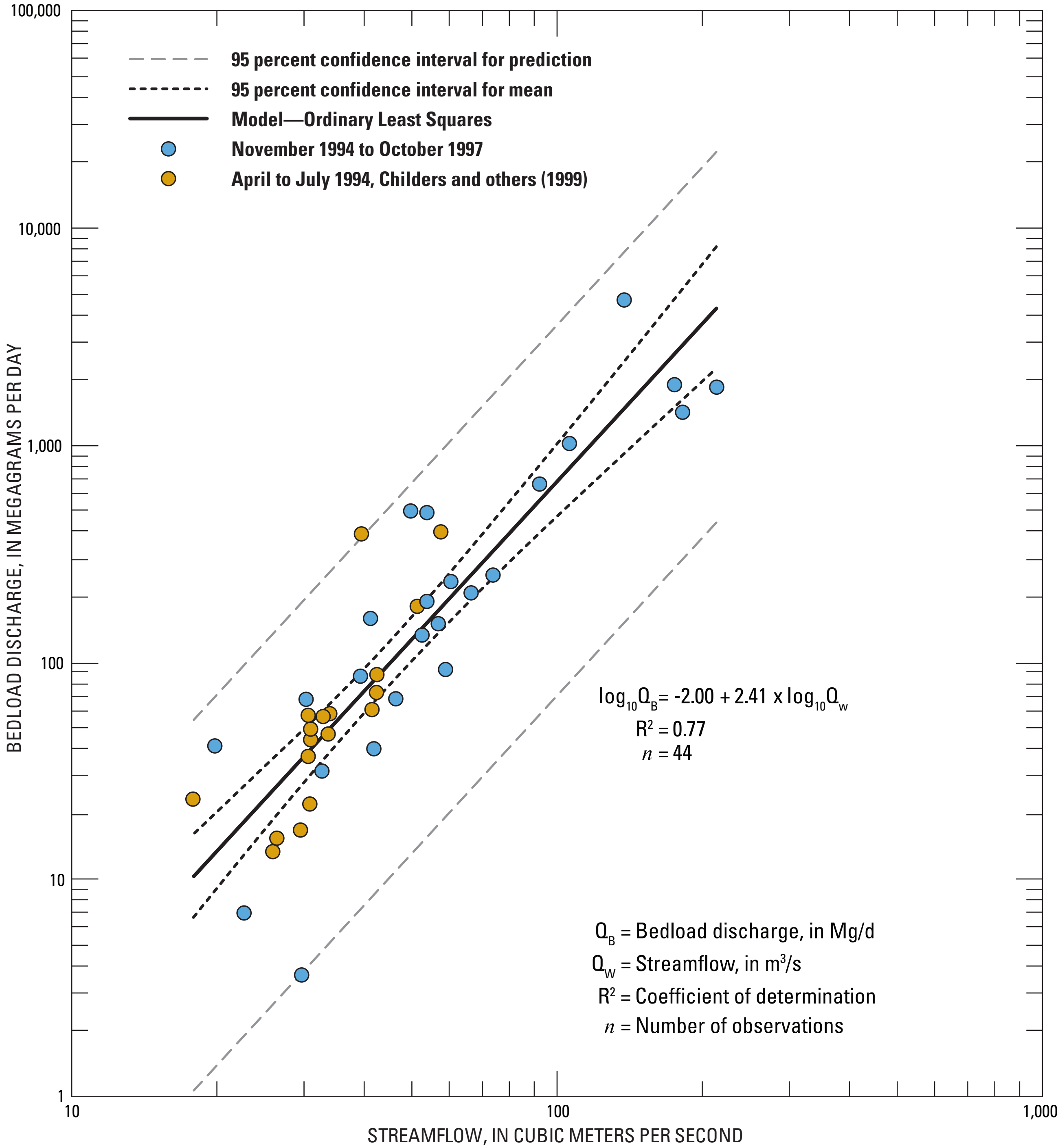


**Figure 7.** Transport curve used to estimate bedload discharge from streamflow, Elwha River above Lake Mills (12044900), Clallam County, Washington, April–July 1994 and November 1994–October 1997.

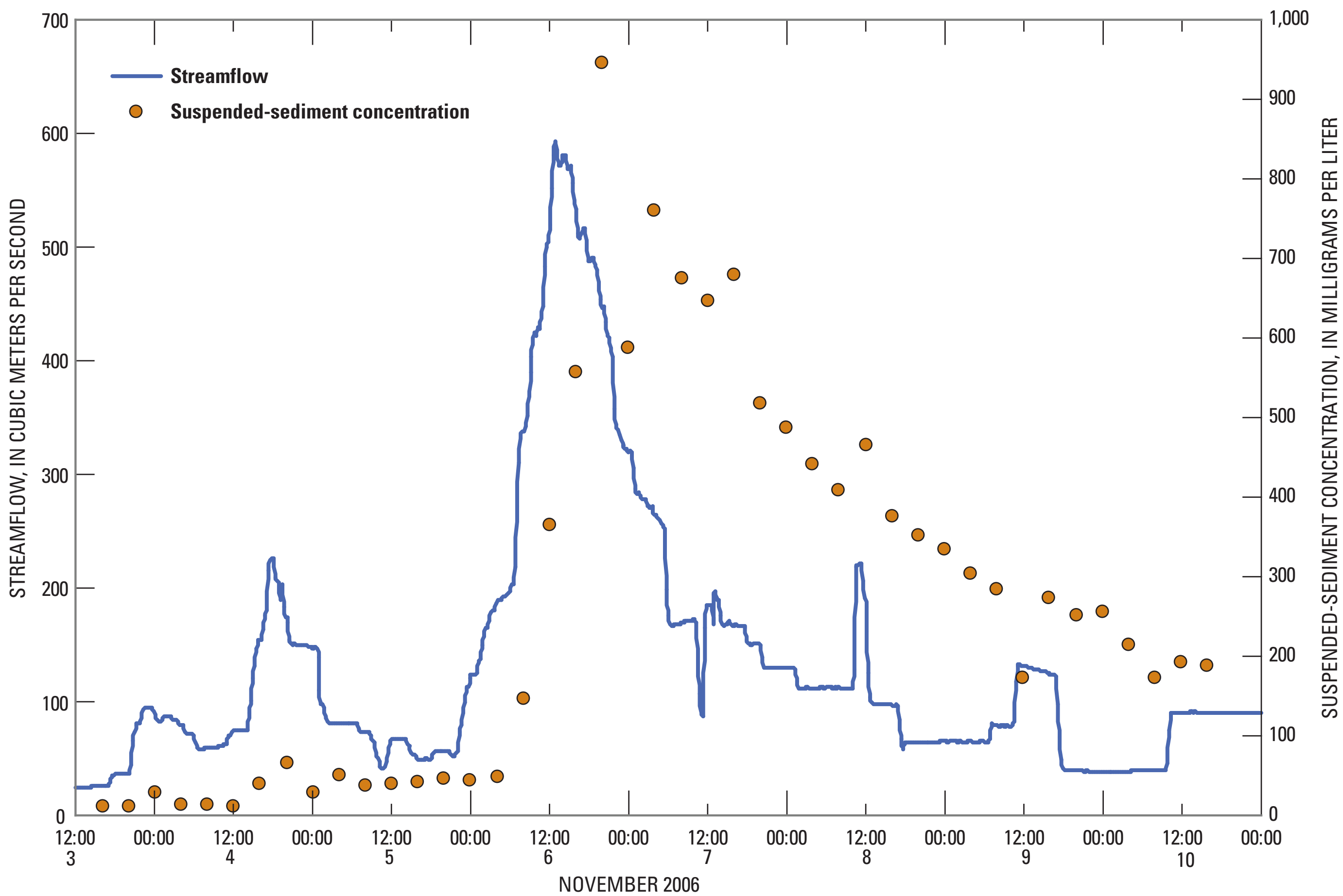


**Figure 8.** Suspended-sediment concentrations and streamflow from samples collected at Elwha River at McDonald Bridge (12045500), Elwha River basin, Clallam County, Washington, November 3–10, 2006.

A limited particle-size analysis was done on 16 automated pump samples collected from December 2005 to January 2006, with suspended-sediment concentrations ranging from 69–454 mg/L. Of these, 14 samples were predominantly fine sediment (less than 0.0625 mm) with an average of 91 percent by mass. The percentage of fine sediment in samples at this site generally was higher than samples collected from the site upstream of Lake Mills, indicating that sand-sized particle settling occurs in Lake Mills.

Suspended-sediment concentrations of samples collected using the EDI method and automated pump sampler were combined in GCLAS with the record of instantaneous streamflow at this gaging station to calculate the daily, monthly, and annual suspended-sediment loads (appendix E).

## Comparisons of Sediment Load and Determination of Trap Efficiency of Lake Mills

Monthly suspended-sediment loads determined at both gaging stations on the Elwha River indicate that most sediment transport occurs during the winter flood season (November–February) with a smaller contribution occurring during mid-summer as a result of higher flows from snowmelt (fig. 9).

At the gaging station upstream of Lake Mills, the annual suspended-sediment load was 186,000 Mg in water year 2006 and 233,000 Mg in water year 2007 (appendix B).

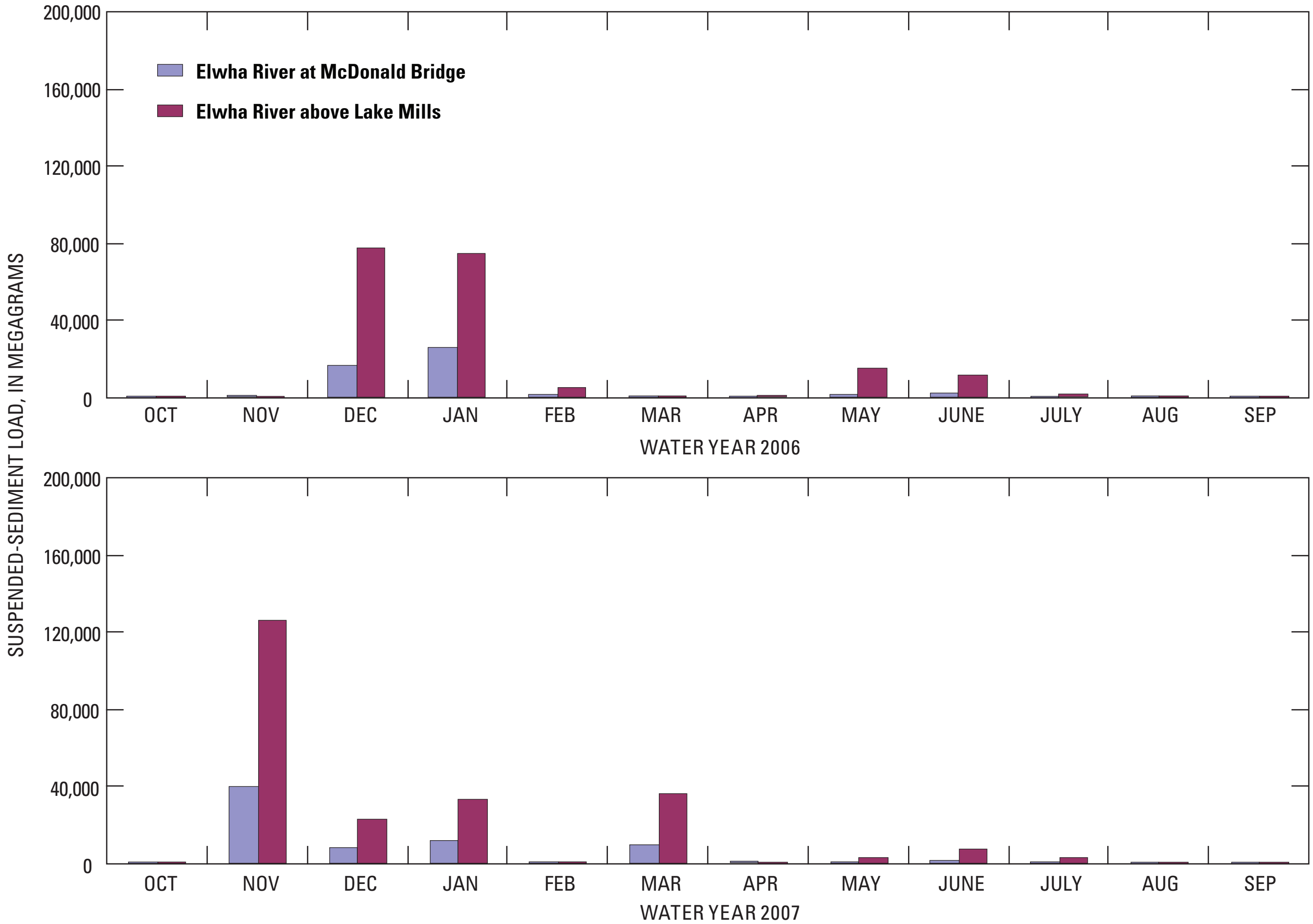


**Figure 9.** Comparison of monthly suspended-sediment loads at Elwha River above Lake Mills (12044900) and Elwha River at McDonald Bridge (12045500), Elwha River basin, Clallam County, Washington, water years 2006 and 2007.

Downstream of Glines Canyon Dam, the annual suspended-sediment load at the McDonald Bridge gaging station was 49,300 Mg in water year 2006 and 75,200 Mg in water year 2007 (appendix E). The suspended-sediment yield for the basin upstream of the gaging station upstream of Lake Mills, calculated from the annual load divided by the drainage area (513 $km^2$), was 363 $Mg/km^2$ for water year 2006 and 454 $Mg/km^2$ for water year 2007.

The ability of a reservoir to force the deposition of suspended particles and accumulate sediment over time can be quantified as the trap efficiency. The trap efficiency of a reservoir can be calculated as:

$$T_E = (Ls_i - Ls_o) / Ls_i \, , \tag{6}$$

where

$T_E$ is the trap efficiency of the reservoir (dimensionless);

$Ls_i$ is the sediment load flowing into the reservoir in megagrams; and

$Ls_o$ is the sediment load flowing out of the reservoir in megagrams.

The trap efficiency for Lake Mills was determined from the annual loads calculated at the gaging stations upstream and downstream of the reservoir. However, because the Lake Mills and McDonald Bridge gaging stations are not immediately upstream and downstream of the dam (4.3 km upstream and 7.6 km downstream, respectively), the additional sediment loads contributed from the drainage areas of these reaches were estimated using the sediment yield determined for the basin upstream of the gaging station upstream of Lake Mills. To estimate the additional loads, the sediment yield was multiplied by the drainage areas associated with the reaches immediately upstream and downstream of the dam (122 and 62 $km^2$, respectively). The resulting estimated load upstream of the dam was added to the annual sediment load at the gaging station upstream of Lake Mills to determine $Ls_i$. The estimated load downstream of the dam was subtracted from the annual load determined at the McDonald Bridge gaging station to determine $Ls_o$. The mean trap efficiency calculated from equation 6 was 0.86 for water years 2006 and 2007.

## Summary

The two dams on the Elwha River in Washington State are scheduled for removal in the near future: the Elwha Dam, which forms Lake Aldwell, and the Glines Canyon Dam, which forms Lake Mills. In an effort to estimate suspended-sediment loads prior to dam removal, the U.S. Geological Survey (USGS) collected suspended-sediment samples during water years 2006 and 2007 at two gaging stations on the Elwha River. One gaging station is in the free-flowing river upstream of Lake Mills and the other gaging station is downstream of Glines Canyon Dam. At the gaging station upstream of Lake Mills, samples of suspended sediment were collected over a range of flows including a large peak in November 2006 when suspended-sediment concentrations exceeded 7,000 milligrams per liter, the highest ever recorded on the river. A limited size analysis of samples collected before and during this flood peak indicated that the percentage of fine sediment (less than 0.0625 millimeters) increased as the flood progressed, likely due to the magnitude and seasonal timing of the flood. Suspended sediment measurements made during this study were combined with previously published measurements made during water years 1995–98 to develop a regression equation for estimating suspended-sediment concentration as a function of streamflow. This equation was used to estimate monthly and annual suspended-sediment loads for water years 2006 and 2007 using the USGS software program Graphical Constituent Loading Analysis Software (GCLAS). Additionally, a regression equation for estimating bedload discharge was developed from measurements made during the Lake Mills drawdown study and measurements made during water years 1995–98. On the basis of these regression equations, a flow-duration approach using the streamflow record upstream of Lake Mills produced an estimate of the average total annual sediment load from the Elwha River into Lake Mills of 327,000 megagrams with a range of uncertainty of +57 to -34 percent (217,000–513,000 megagrams) at the 95 percent confidence level. Of this total, 77 percent was estimated suspended-sediment load and 23 percent was estimated bedload.

At the McDonald Bridge gaging station downstream of Glines Canyon Dam, daily suspended-sediment samples were obtained with an automated pump sampler. These samples were used in Graphical Constituent Loading Analysis Software (GCLAS) to compute a record of daily, monthly, and annual suspended-sediment loads. At this site, a time lag of about 8 hours was observed between sediment concentration and streamflow peaks due to the slower transport of sediment through the reservoir relative to the propagation of the flood peak.

A comparison between the annual suspended-sediment loads at both gaging stations determined loads of 186,000 megagrams and 233,000 megagrams in water years 2006–07 upstream of Lake Mills and 49,300 megagrams and 75,200 megagrams, respectively, for the same period downstream of Glines Canyon Dam. Substantially more sediment load measured upstream compared with downstream of the reservoir indicates the extent to which Lake Mills traps and accumulates sediment. A trap efficiency of 0.86 was determined for the Lake Mills reservoir, based on suspended-sediment loads upstream and downstream of the lake. These pre-dam-removal estimates of suspended-sediment loads and sediment-discharge relations provide a baseline of data that will be useful to planners and scientists monitoring geomorphic and habitat changes in the river as it reaches a dynamic equilibrium following the removal of the dams.

## References Cited

Bragg, H.M., Sobieszczyk, S., Uhrich, M.A., and Piatt, D.R., 2007, Suspended-sediment loads and yields in the North Santiam River basin, Oregon, water years 1999-2004: U.S. Geological Survey Scientific Investigation Report 2007-5187, 26 p.

Childers, Dallas, Kresch, K.L., Gustafson, S.A., Randle, T.J., Melena, J.T., and Cluer, Brian, 1999, Hydrologic data collected during the 1994 Lake Mills drawdown experiment, Elwha River, Washington: U.S. Geological Survey Water-Resources Investigations Report 99-4215, 115 p.

Edwards, T.K., and Glysson, D.G., 1999, Field methods for measurement of fluvial sediment: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. C2, 89 p.

Glysson, D.G., 1987, Sediment-transport curves: U.S. Geological Survey Open-File Report 87-218, 47 p.

Guy, H., 1970, Fluvial sediment concepts: U.S. Geological Survey Techniques of Water-Resources Investigations, book 3, chap. C1, 55 p.

Helsel, D.R., and Hirsch, R.M., 1992, Statistical methods in water resources: New York, Elsevier, 522 p.

Julien, P.Y., 1998, Erosion and sedimentation (2nd ed.): New York, Cambridge University Press, 280 p.

Koltun, G.F., Eberle, Michael, Gray, J.R., and Glysson, D.G., 2006, User's manual for the Graphical Constituent Loading Analysis System (GCLAS): U.S. Geological Survey Techniques and Methods 4-C1, 51 p.

Munn, M.D., Black, R.W., Haggland, A.L., Hummling, M.A., and Huffman, R.L., 1998, An assessment of stream habitat and nutrients in the Elwha River basin—Implications for restoration: U.S. Geological Survey Water-Resources Investigation Report 98-4223, 38 p.

Searcy, J.K., 1959, Flow duration curves *in* Manual of hydrology—Part 2, Low-flow techniques: U.S. Geological Survey Water Supply Paper 1542-A, 33 p.

Tabor, R.W., and Cady, W.M., 1978, Geologic map of the Olympic peninsula: U.S. Geological Survey IMAP, I-994, scale 1:125,000.

U.S. Department of the Interior, 1995, Elwha River ecosystem restoration, final environmental impact statement NPS D-253A: U.S. Department of the Interior, National Park Service, 215 p.

U.S. Geological Survey, 2008, National Water Information System: U.S. Geological Survey database, accessed June 6, 2008, at http://waterdata.usgs.gov/wa/nwis

Wiggins, W.D., Ruppert, R.R., Smith, L.L., Reed, L.E., Hubbard, L.E., and Courts, M.L., 1995, Water resources data, Washington, water year 1995: U.S. Geological Survey Water-Data Report WA-95-1, 456 p.

Wiggins, W.D., Ruppert, R.R., Smith, L.L., Reed, L.E., Hubbard, L.E., and Courts, M.L., 1996, Water resources data, Washington, water year 1996: U.S. Geological Survey Water-Data Report WA-96-1, 494 p.

Wiggins, W.D, Ruppert, R.R., Smith, L.L., Reed, L.E., and Courts, M.L., 1997, Water resources data, Washington, water year 1997: U.S. Geological Survey Water-Data Report WA-97-1, 528 p.

# Appendixes

Data files that contain suspended-sediment measurements and loads (appendixes A–D) and flow-duration/sediment rating curve calculations (appendix E) are presented in five Microsoft© Excel spreadsheets. The appendixes can be accessed and downloaded at URL http://pubs.usgs.gov/sir/2009/5221/.

**Appendix A.** Suspended-Sediment Measurements at U.S. Geological Survey Gaging Station Elwha River Above Lake Mills (12044900), Elwha River Basin, Clallam County, Washington, Water Years 1995–98

**Appendix B** Estimates of Monthly and Annual Suspended-Sediment Load at U.S. Geological Survey Gaging Station Elwha River Above Lake Mills (12044900), Elwha River Basin, Clallam County, Washington, Water Years 2006–07

**Appendix C.** Bedload Measurements at U.S. Geological Survey Gaging Station Elwha River Above Lake Mills (12044900), Elwha River Basin, Clallam County, Washington, Water Years 1995–98

**Appendix D.** Flow-Duration/Sediment Rating Curve Calculations for Determining Estimated Total Annual Sediment Load into Lake Mills, Elwha River Basin, Clallam County, Washington

**Appendix E.** Daily, Monthly, and Annual Suspended-Sediment Load at U.S. Geological Survey Gaging Station Elwha River at McDonald Bridge (12045500), Elwha River Basin, Clallam County, Washington, Water Years 2006–07

This page intentionally left blank.

Publishing support provided by the U.S. Geological Survey
Publishing Network, Tacoma Publishing Service Center

For more information concerning the research in this report, contact the
Director, Washington Water Science Center
U.S. Geological Survey, 934 Broadway — Suite 300
Tacoma, Washington 98402
http://wa.water.usgs.gov

Curran and others—**Estimates of Sediment Load Prior to Dam Removal in the Elwha River, Clallam County, Washington**—Scientific Investigations Report 2009–5221