CHAPTER 4.
SEDIMENT TRANSPORT AND DEPOSITION

INTRODUCTION

Purpose

An analysis was performed to characterize sediment conditions of the Lower Puyallup River, quantify sediment inflow to the study reach, assess recent changes in the river cross section due to sediment deposition and aggradation, and develop a numerical sedimentation model for forecasting future deposition along the Lower Puyallup. A HEC-RAS sediment transport model (Hydrologic Engineering Center, Version 4.0, 2006) was developed to predict the location, volume and depth of sediment deposition or erosion through the study reach.

The primary objective of the sediment investigation was to provide a 50-year forecast of bed adjustments related to sediment deposits that may affect the river channel's flood carrying capacity. The sediment model was developed and calibrated using information from surveyed channel cross sections, site specific measurements of sediment transport rates, measurements of existing bed material characteristics, and analysis of hydrologic conditions. It was then used to estimate future channel aggradation in the study area. The results provide estimates of future channel geometry, which when input into the HEC-RAS hydraulic model reveal how flood profiles are likely to be affected by sediment deposition 50 years in the future. The analysis assumes that no significant sediment maintenance activity (i.e. channel dredging) occurs during the 50-year forecast period.

Prior Studies

Previous sediment and hydraulic studies of the Puyallup River include the following:

- Flood-Carrying Capacities and Changes in Channels of the Lower Puyallup, White, and Carbon Rivers in Western Washington (USGS, 1988)
- Sediment Transport in the Lower Puyallup, White and Carbon Rivers of Western Washington (USGS, 1989)
- Flood Insurance Mapping Study for Puyallup River (FEMA, 2007).

Information presented in these studies includes surveyed channel cross sections, measurements of sediment transport rates, measurements of bed material characteristics and analysis of hydrologic and hydraulic conditions on the Lower Puyallup River.

Definitions

Sediment is present in the Puyallup River in a wide range of particle sizes. Coarse gravels and cobbles make up the majority of the channel bed upstream of the confluence with the White River. Sands, silts, and clays tend to deposit in the lowermost, tidally influenced reach of the river. The total sediment load of a stream consists of sediment from the following sources:

- Wash load sediment is the finest portion of sediment, generally silt and clay, that is carried through the system with inappreciable quantities found in the channel bed. Typically wash-load sediments are derived from watershed soil erosion process (rill and gully erosion) and channel bank erosion. The discharge of wash load depends primarily on the rate of supply from the watershed and is not generally correlated with flow characteristics.

- Bed material load sediment is sediment found in the bed of the channel. The process of transport can be through either bed load or suspended load transport. Typically, the total magnitude of bed material load increases with increasing stream flow. Finer bed material load is transported as suspended sediment load and coarser sediments are transported as bedload. Larger bed materials (i.e. gravels and cobbles) can be mobilized as flow strength increases.

The following are the two primary modes of sediment transport:

- Bedload transport is sediment that is moving on or near the bed by rolling, bouncing or sliding. Movement can be either continuous or intermittent but is generally much slower than the mean velocity of the stream. In the upper Puyallup River watershed, bedload consists primarily of coarse sands, gravels and cobbles.
- Suspended sediment is supported by the turbulent motion in the stream flow and is transported at a rate approaching the mean velocity of flow. In the Puyallup River watershed, suspended sediment consists primarily of fine sands, silts and clays.

The boundary between bedload and suspended load can change between low flows and high flows as material that was being transported as bedload at low flows becomes suspended when velocities and turbulence increase sufficiently during high flows.

EXISTING CONDITIONS

River Morphology

The sediment model was developed for the lower 37,800 feet of the Puyallup River, from Commencement Bay to a few miles upstream of USGS Gage 12101500 (Puyallup River at Puyallup). Lower Puyallup streambed elevations range from -10 feet (NAVD88) at the river mouth to about 25 feet (NAVD88) near the confluence with the White River (RM 10.1). Slopes range from 0.00035 feet/foot near the mouth to 0.0006 feet/foot near the White River confluence, with a break in gradient near RM 3.75. Samples indicate that bed materials in the study reach are primarily medium and fine sand with gravel. Field observations show that the median particle size decreases in the downstream direction.

Surveyed Cross Sections

Five sets of surveyed cross sections were used to estimate the amount of deposition and/or erosion that has occurred in the study reach of the Lower Puyallup River over the past 27 years (USGS, 1980; W&H Pacific, 2001; COE, 2001; NHC**,** 2002; Minister and Glaeser, 2007). Due to the dates in which data was collected, two slightly different time intervals were examined to estimate the average rates of deposition and erosion: 1980 to 2002 and 2002 to 2007 for the lower 30,000 feet of the study reach and 1980 to 2001 and 2001 to 2007 for the remainder.

Survey points in the USGS 1980, W&H Pacific 2001 and NHC 2002 surveys were originally referenced to NGVD29 and were converted to NAVD88 by adding 3.49 feet. The COE 2001 survey was referenced to the mean lower low water (MLLW) elevation and was converted to NAVD88 by subtracting 2.68 feet. All surveyed data was spatially referenced to Washington State Plane South NAD 83/91.

Surveyed cross section comparison plots are attached in Appendix B. Appendix C provides a channel stationing baseline indicating the channel section identifier.

Bed Material

Bed material samples were collected throughout the study reach during a field reconnaissance in May 2007. Samples were collected by boat from the channel thalweg (the lowest-elevation point of each cross section) at approximately 1 mile increments starting in Commencement Bay and ending at the confluence with the White River. Each sample was collected with a drag sampler consisting of a 6-inch-diameter, 2-foot-long steel pipe with one end open as a cutting edge. The other end had a removable filter to allow water to drain out while lifting the sampler from the water. Each sample was taken by lowering the sampler to the channel bottom then dragging it along the channel bed. When retrieving the sampler, the boat was held stationary while the sampler was brought up slowly to ensure that no fines were washed out. Once the sampler was brought on deck, time was allowed for excess water to drain through the filter, then a representative subsample of the bed material was placed into a plastic bag which was sealed and labeled for shipment for laboratory sieve analysis. Laboratory test results are provided in Appendix D. Each of the 10 sampling sites was entered in a sample log with a corresponding handheld GPS waypoint; sampling locations are provided in Appendix C.

Subsurface samples were collected to characterize the materials in transport during bed mobilization flood events (Parker 1991). Subsurface samples were analyzed for grain size distribution by Shannon & Wilson, Inc. Laboratory test results are provided in Appendix D.

Figures 4-1 and 4-2 show the resultant bed material size distributions used for the HEC-RAS simulations. Figure 4-1 shows the bed material size distribution for the lower 6.87 miles. This size distribution was adopted for the sediment inflow size distribution as well. The sediment is characterized as a poorly graded sand, with a median particle diameter of 0.35 mm (medium sand). Figure 4-2 shows the bed material size distribution for the upper 3.32 miles. The sediment has a bimodal distribution containing a poorly graded fine sand and a poorly graded gravel.

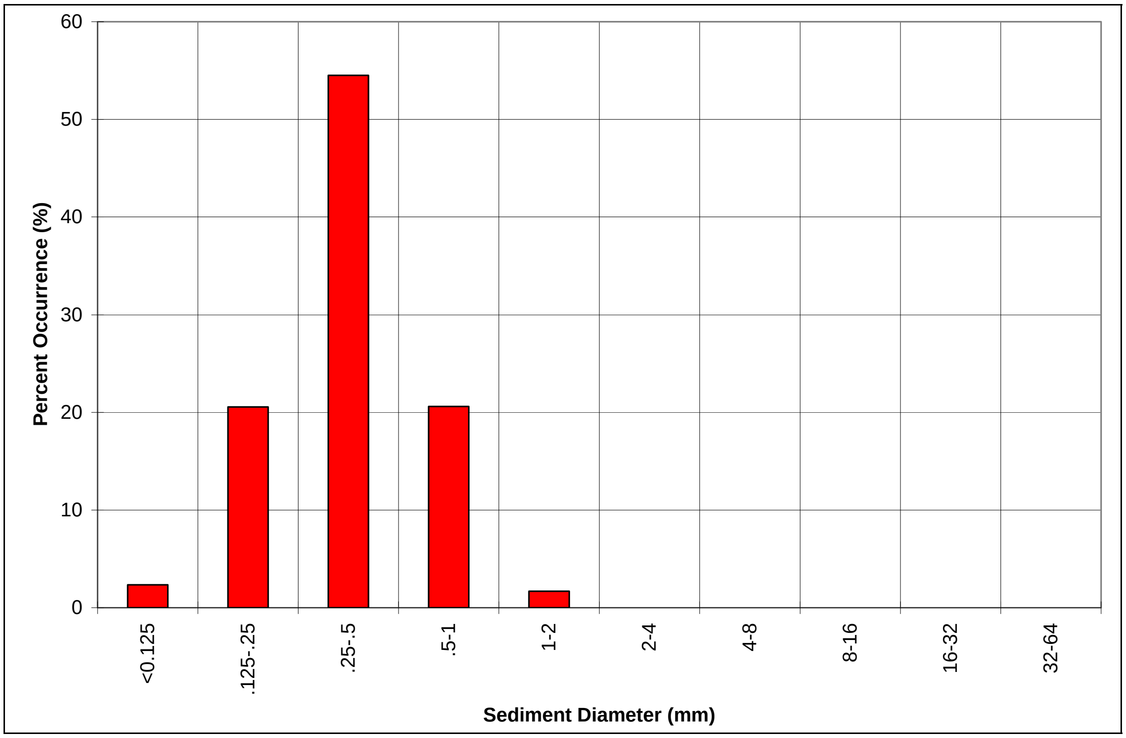

Figure 4-1. Bed Material Characteristics for Lower 6.87 Miles of Study Reach

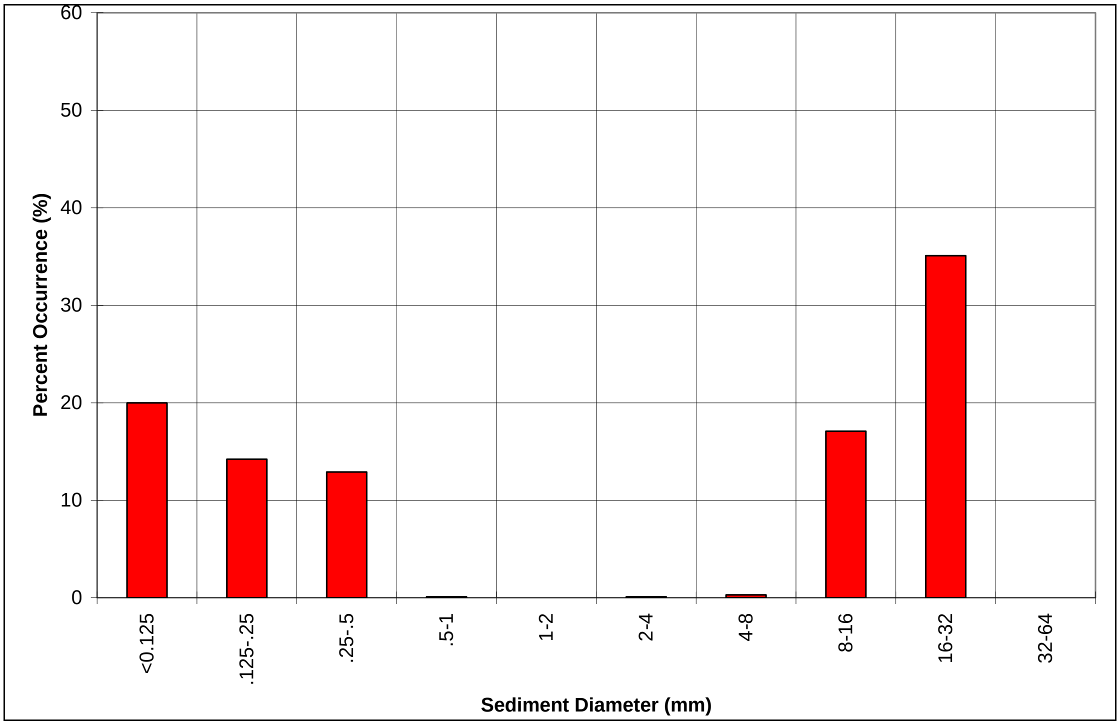

Figure 4-2. Bed Material Characteristics for Upper 3.32 Miles of Study Reach

Observed Sediment Load

Figure 4-3 shows a sediment rating plot created from suspended sediment discharges (tons/day) and stream flow (cfs) both recorded at USGS Gage 12101500 from January 1978 through July 1994. Only the fraction of sediments coarser than 0.063 mm (very fine sand) is plotted, because this closely matches the minimum size of the sampled bed material. It is assumed that the finer silts and clays do not deposit but are carried downstream to Commencement Bay. This information was used, together with the flow duration curve presented in Chapter 2, to estimate the initial sediment load in the HEC-RAS model.

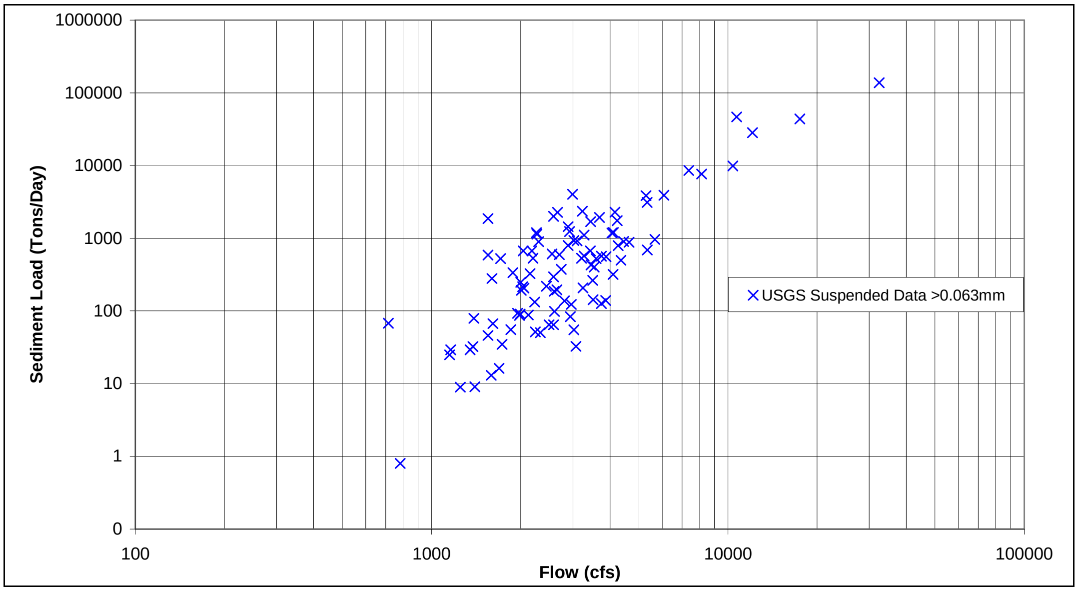

Figure 4-3. Sediment Rating Curve for Puyallup River at Puyallup Gage (12101500), 1978—1994

Stage-Discharge Rating Curve Shifts

Shifts in a river's stage-discharge relationship over time are good indicators of changes in channel geometry. Such shifts are best detected from regular discharge field measurements and become evident when several measurements deviate from the established rating curve. Typically, if a single discharge measurement is within 5 percent of the discharge value indicated by an established rating curve, the measurement is considered to be a verification of the established curve. If several consecutive random measurements meet the 5-percent criterion but all plot on one side of the established rating curve, they may be considered to define a period of shifting. Figure 4-4 shows three stage-discharge relationships for USGS Gage 12101500 (1937 to 1990, 1990 to 2000, and 2000 to 2007). This reveals an approximately 1-foot increase in stage since 1990, which is likely the result of sediment deposition in the river channel at and downstream of the gage.

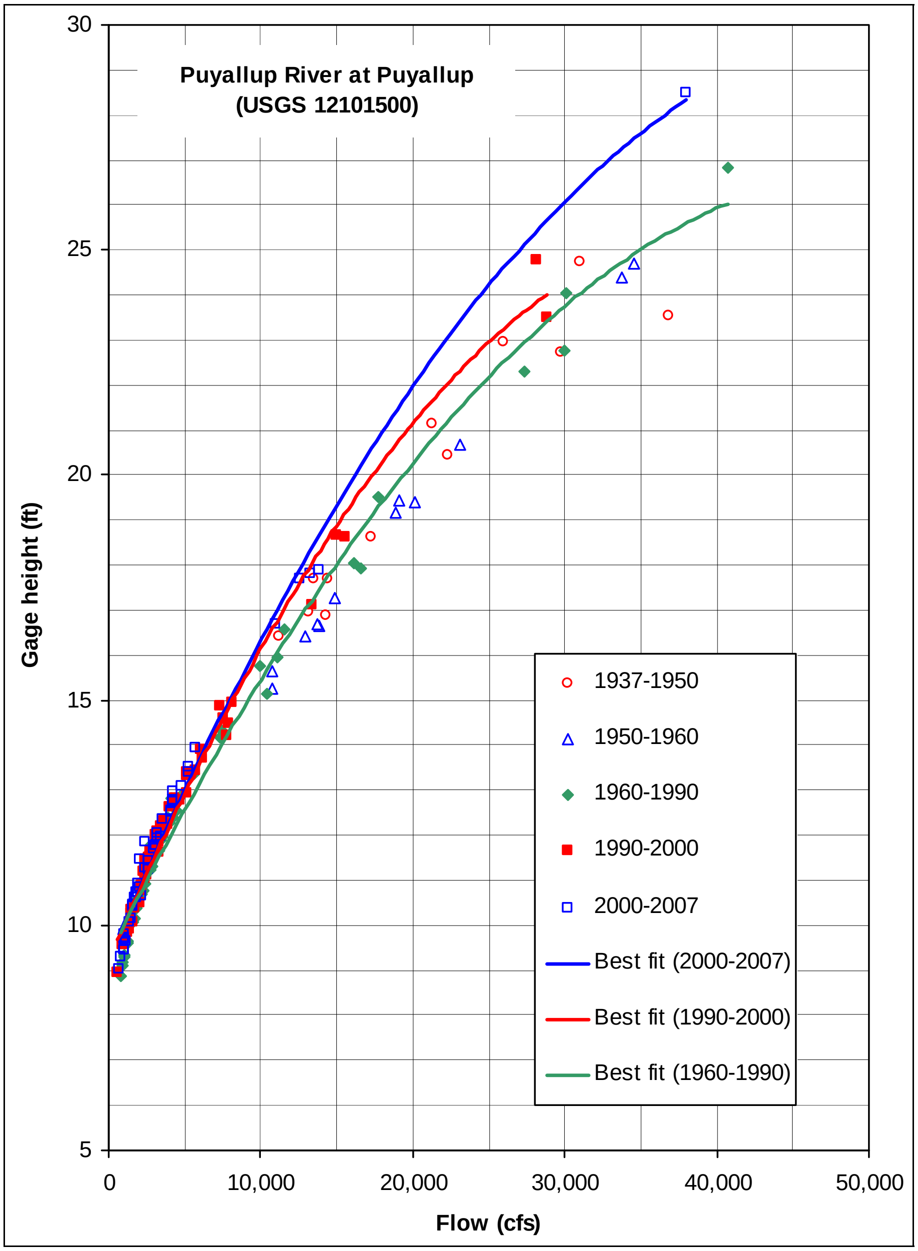

Figure 4-4. Stage-Discharge Curve for Puyallup River at Puyallup Gage (12101500)

Gage height recordings and corresponding flow measurements taken at USGS Station 12101500 from 1985 to 2007 were compared to the rating curves in Figure 4-4 to determine the shift in gage height. Figure 4-5 shows the calculated gage height shift along with the corresponding flow measured at the USGS gage. Short-term fluctuations in the gage height shift correlate with low and high flows. Generally, periods of low flows correlate with aggradation and periods of high flows correlate with erosion. The longer-term rise in gage height shift can be attributed to long-term deposition of sediment at the gage.

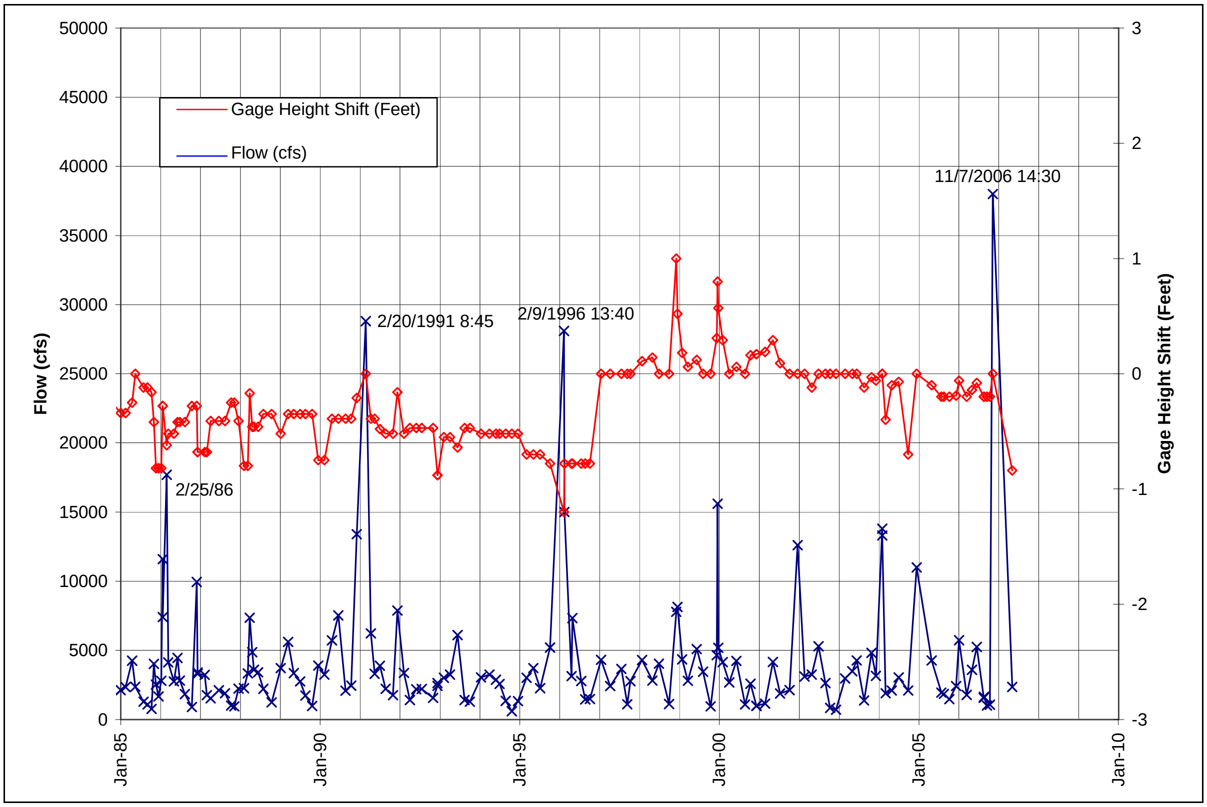

Figure 4-5. Gage Height Shift for Puyallup River at Puyallup Gage (12101500)

Tidal Stage Characteristics

Downstream water surface elevations in the Puyallup River are controlled by the tidal elevation at the river's mouth in Commencement Bay. Time-variant water surface elevations can be specified as a function of time in HEC-RAS 4.0. Tidal stage elevations for the sedimentation assessment were based on tidal records at the National Oceanic and Atmospheric Administration gage in Tacoma (NOAA Station 9446484). The tidal elevations recorded at this gage yield the following approximate tidal stage elevations for the mouth of the Puyallup River (NAVD 88):

- Mean High Water: 8.27 feet
- Mean Sea Level: 4.22 feet
- Mean Low Water: 0.17 feet.

These elevations were specified to occur within each flow increment in the sediment model simulations. To simulate the effects of the varying tidal elevations in the quasi-unsteady hydraulic simulations of the HEC-RAS 4.0 model, the mean high water and mean low water elevations were specified for 25 percent of the duration for a given flow as determined in the flow duration analysis described in Chapter 2. The mean sea level was specified for the remaining 50 percent of the flow duration.

DESCRIPTION OF SEDIMENT MODEL

HEC-RAS 4.0 is the most recent release of the Hydrologic Engineering Center's (HEC) River Analysis System (RAS). It incorporates much of the one-dimensional sediment transport routing of the HEC-6 "Scour and Deposition in Rivers and Reservoirs" code (Hydrologic Engineering Center, 1993) into the graphical HEC-RAS interface. The HEC-RAS 4.0 model was used to quantify the sedimentation regime of the Puyallup River and the temporal and spatial characteristics of sediment transport, erosion and deposition in the study reach. Hydraulic computations within the model were calibrated to the hydraulic conditions of the Puyallup River. Sediment transport computations were calibrated to measured channel aggradation for the lower 4 miles of the river.

HEC-RAS 4.0 is a one-dimensional, movable boundary, open channel flow model developed to simulate streambed profile changes resulting from varying river flow and tailwater conditions. The model assesses spatial and temporal variations in non-equilibrium sediment transport conditions in alluvial channels due to imbalances of sediment inflow, bed material characteristics and sediment transport capacity. The model is based on one-dimensional, gradually varied flow hydraulics and sediment transport theory and is capable of calculating sedimentation in dendritic, closed loop and distributary networks of river systems.

Model Assumptions

In all HEC-RAS models, geometry is modeled by cross sections and hydraulic roughness is assigned by either a Manning's n value or a Chezy coefficient. A flow hydrograph is segmented into a series of steady flow events of variable duration (quasi-steady). For each flow sequence, the one-dimensional conservation of energy equation is solved to determine the water surface profile and pertinent hydraulic parameters such as energy slope, velocity, depth, hydraulic roughness and width at each cross section. Sedimentation processes (erosion, entrainment, transportation, deposition and compaction of sediment particles) are computed at each cross section by solving the Exner sediment continuity equation and a user-selected sediment transport function from among the following options:

- Ackers-White (1973)
- England and Hansen (1967)
- Laursen-Copeland (1968/1989)
- Meyer-Peter and Muller (1948)
- Toffaleti (1968)
- Yang (1973/1984)
- Wilcock (2001)

The Laursen-Copeland transport function was selected to compute bed material sediment transport capacity for the Lower Puyallup River. This transport function is a total load formula developed for computing sediment transport of coarse silt to gravel sized sediments. It was chosen based on experience in sedimentation modeling studies and on its ability to accurately replicate the sediment load rating curve shown in Figure 4-3.

Various supporting equations are required, such as bed material sorting processes, armoring processes, particle entrainment, particle deposition and consolidation of mixtures of bed deposits. The basis for this solution of the non-equilibrium condition of sediment transportation is Thomas's extension of the Einstein model of the equilibrium condition. The following assumptions are made in deriving and applying these equations:

- The channel is sufficiently straight and uniform in the reach so that the flow characteristics may be physically represented by a one-dimensional model.
- The velocity is uniformly distributed over the cross section.
- Hydrostatic pressure prevails at every point in the channel.

- The water surface slope is small.
- The density of the sediment-laden water is constant over the cross section.
- The unsteady flow resistance coefficient is the same as for steady flow in alluvial channels (estimated from resistance equations applicable to alluvial channels or from field surveys).

The numerical technique used to solve the one-dimension conservation of energy equation is commonly called the standard step method. An explicit six-point finite difference method is used to solve the sediment conservation of mass equation as functions of time and sediment transport rates. These rates, combined with the duration of the flow, allow for volumetric accounting of sediment within each reach. The amount of scour or deposition within each reach is computed and the cross section geometry is then adjusted accordingly. The computations proceed to the next flow in the sequence and the cycle is repeated beginning with the updated geometry. The sediment calculations are done by grain size fraction, thereby allowing for the simulation of hydraulic sorting and armoring. Potential sediment transport characteristics and rates, including sediment load, gradation of the load, gradation of the bed surface materials and depth of scour or deposition, are computed at each cross section.

The conservation of mass of bed material relationship (the Exner equation), requires that the physical dimensions, such as width and depth of the sediment control volume be specified. The vertical thickness was set to an erodible depth of 5 feet throughout the modeled reach. Lateral limits for erosion and deposition were specified to equal the wetted perimeter of a cross section and not to exceed the channel bank stations.

Model Limitations

Limitations inherent in the sediment transport module of HEC-RAS 4.0 are as follows:

- The model is based on one-dimensional gradually varied flow hydraulics and sediment transport theory.
- There is no provision for simulating the development of channel meanders or specifying lateral distributions of sediment load across a cross section.
- The processes and loading contributions due to bank caving are calculated by empirical bank erosion rate related methods rather than by the physics of soil mechanics.

Although these limitations may inhibit the model’s applicability for quantifying some selected morphological adjustment processes, the limitations do not limit the model’s applicability for quantifying sedimentation dynamics on the Lower Puyallup River system for assessing long term changes in flood profile elevations.

Boundary Conditions

HEC-RAS 4.0 computes and simulates the following:

- The hydraulics of gradually varied open-channel flow
- Conservation of mass of sediment transport, by updating the channel bed elevation and bed material grain size distribution over time in response to the inflowing sediment load and local sediment transport capacity
- A coupling of the resultant non-equilibrium changes in channel geometry with the hydraulic characteristics of the channel.

To accomplish these computations, boundary conditions are specified at inflow and outflow control points that bracket the study area. Flow rate, sediment concentration and grain size distribution are specified at all inflow locations. The controlling water surface elevation at the downstream limit of the model is specified for the selected time period for simulation as well. Internal boundary conditions are specified at specific cross-sections to define cross-sectional geometry, reach lengths between cross-sections, hydraulic roughness, bed material grain size distribution and limits of sediment deposition and erosion. The following data were used for the Lower Puyallup River model:

- **Geometry**—A calibrated model geometry used for the FEMA (2007) flood mapping study on the Puyallup River was used as the baseline for this study. The geometry data used was surveyed by W&H Pacific in 2001 and measured by NHC in 2002**.**
- **Flow rates**—Historical flows measured by the USGS at the Puyallup River gage near Puyallup (Station 12101500) were used to identify the temporal variability of flow duration characteristics of the Puyallup River. Detailed discussion of the historical flow data is provided in Chapter 2.
- **Sediment Concentration**—Historical suspended sediment loads measured at USGS Gage Station 12101500 (Figure 4-3) were used as an initial assumption for the sediment inflow boundary condition.
- **Starting Water Surface Elevation**—The model's downstream boundary is the mouth of the Puyallup River at Commencement Bay. Tidal stage characteristics at the mouth were developed from tidal records from the NOAA tidal gage at Commencement Bay (NOAA Station 9446484).
- **Bed Material Grain Size Distribution**—Bed materials throughout the study reach of the Puyallup River were sampled in May 2007 to characterize the longitudinal variation of grain size distribution.
- **Hydraulic Calibration and Model Adjustment Data**—The hydraulic calculations in HEC-RAS 4.0 were compared with results from the calibrated HEC-RAS 3.1.3 model for the 10-, 50- and 100-year recurrence interval flow (FEMA, 2007).
- **Sedimentation Calibration and Model Adjustment Data**—Sediment inflow quantities, bed sediment characteristics, and sediment transport functions were adjusted based on field observations of bed material distributions and measured sediment erosion and deposition rates on the Puyallup River.

MODEL ADJUSTMENT AND VERIFICATION

Hydraulic Model

Hydraulic model adjustments primarily consist of adjusting effective conveyance limits, Manning's n values, and expansion and contraction energy loss coefficients to obtain reasonable agreement between measured and computed hydraulic characteristics.

The calibrated hydraulic model from the FEMA (2007) floodplain study was used as a basis for this sedimentation modeling study. The geometry was adjusted to incorporate the lower 7.15 miles of the Lower Puyallup. Bridge sections were modified as needed to properly simulate hydraulic losses and sediment transport through the bridge sub-sections. To account for the hydraulic effects of bridges, blocked obstructions replaced bridge piers and the Manning's n coefficient was adjusted to obtain hydraulic characteristics similar to those in the original model.

Figures 4-6 through 4-8 compare the water surface elevations computed with the FEMA (2007) hydraulic model geometry to the water surface elevations computed with the sedimentation model geometry for the 10-, 50- and 100-year events. Overall, differences in water surface elevations from the original and adjusted model were negligible in the modeled reach.

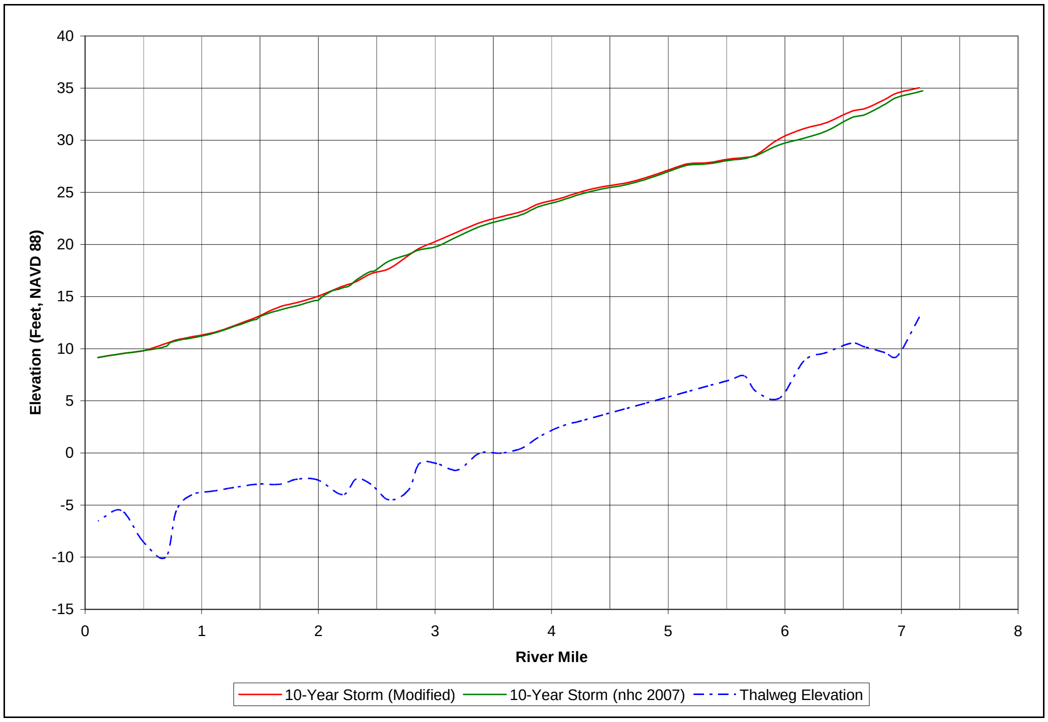

Figure 4-6. Comparison of Adjusted Geometry to Original Geometry for 10-Year Flood

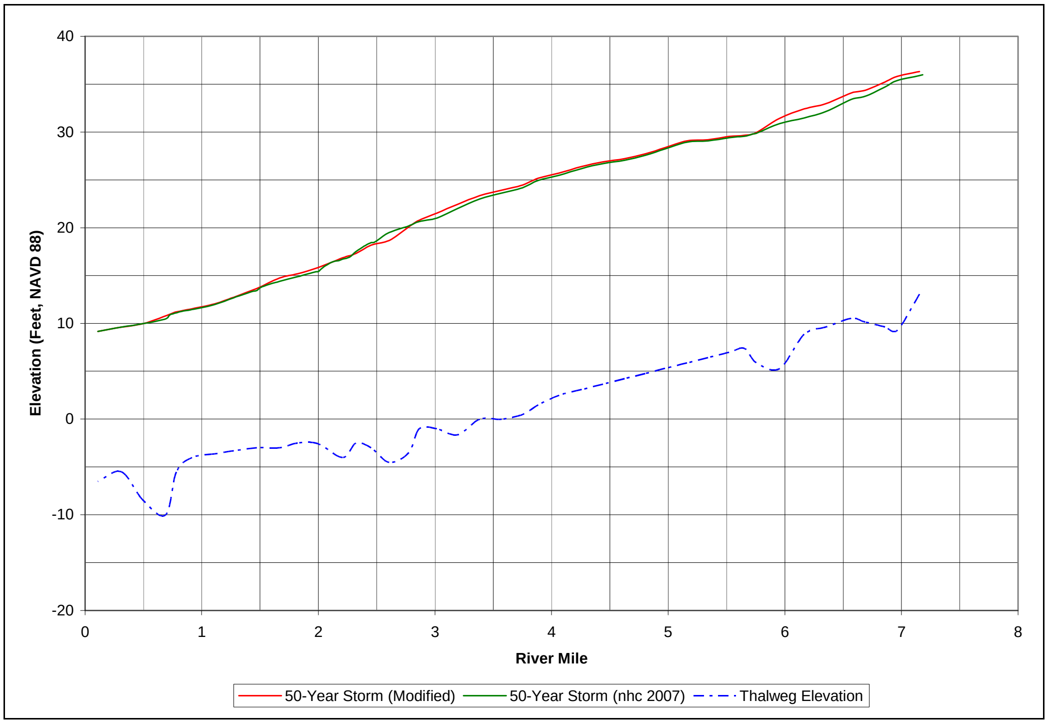

Figure 4-7. Comparison of Adjusted Geometry to Original Geometry for 50-Year Flood

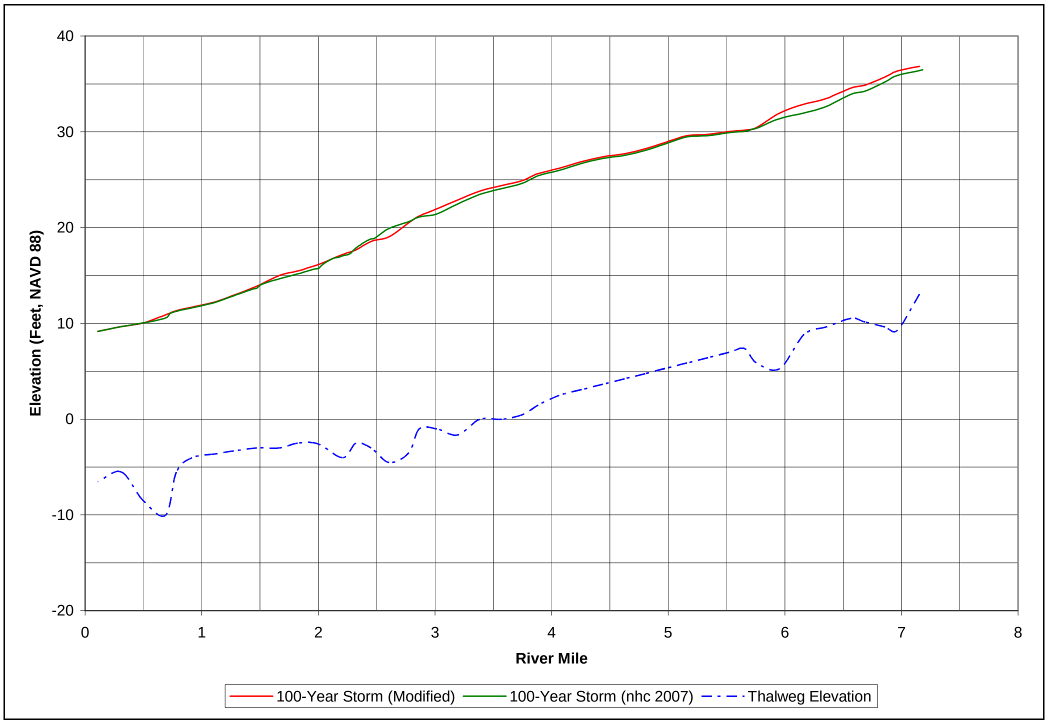

Figure 4-8. Comparison of Adjusted Geometry to Original Geometry for 100-Year Flood

The last adjustment was the addition of a simplified “inflow” reach from RM 7.15 (STA 377+50) to RM 10.18 (STA 537+50), which was adjusted to maintain a constant cross-sectional shape and bed slope, typical of the uppermost sections in the vicinity of STA 377+50. This inflow reach provides sufficient distance for developing a sediment inflow in equilibrium with the bed material and hydraulic conditions at the upstream boundary of the study area.

Sedimentation Model

Sedimentation model adjustment consists of adjusting sediment inflows to obtain reasonable agreement between measured and modeled sediment deposition and erosion. To determine historical locations and quantities of sediment deposition and erosion, an analysis of historical cross-sectional survey data and a field reconnaissance were performed. Using data from the 2002 NHC survey and the 2007 Minister and Glaeser survey, 29 cross-sections—from RM 0.20 (STA 10+75) to RM 9.63 (STA 508+25)—were compared. Changes in average bed elevation from erosion and deposition were calculated for each cross-section. Depositional volumes were computed using the end area approach, and bed level surveys were extrapolated to channel banklines if bed coverage was incomplete. Surveyed cross section comparison plots are located in Appendix B.

The HEC-RAS 4.0 model was then run using flow rates recorded at USGS Gage Station 12101500 for the same time period as the surveyed cross sections (April 2002 to March 2007). By slightly adjusting the sediment rating curve developed from the USGS field measurements, a close agreement was obtained between the measured and modeled changes in bed elevation caused by sediment deposition. Table 4-1 compares the measured and computed sediment deposition values. Figure 4-9 shows the adjusted sediment inflow rating curve, which fits well with the USGS field measurements. Figure 4-10 compares measured deposition to modeled deposition for each modeled cross section, again demonstrating reasonable agreement between measured and computed values.

TABLE 4-1.
COMPARISON OF MEASURED DEPOSITION TO SIMULATED DEPOSITION

River		Deposition[a] (Feet)		River		Deposition[a] (Feet)	
Mile	Station	Measured	Modeled	Mile	Station	Measured	Modeled
0.204	10+75	1.0	0.6	2.917	154+00	1.0	1.5
0.388	20+50	0.3	1.0	3.286	173+50	1.1	1.3
0.582	30+75	0.7	1.2	3.475	183+50	1.3	1.3
0.720	38+00	1.4	1.7	3.651	192+75	1.3	1.1
0.810	42+75	2.0	2.9	3.788	200+00	1.0	1.4
1.411	74+50	1.3	0.5	3.958	209+00	0.9	1.2
1.567	82+75	1.2	1.0	5.653	298+50	0.2[b]	0.1
1.719	90+75	1.4	1.9	6.065	320+25	0.4[b]	-0.1
1.870	98+75	1.1	1.2	6.468	341+50	0.2[b]	0.0
2.074	109+50	1.6	1.8	6.866	362+50	0.4[b]	0.0
2.221	117+25	1.0	0.7	7.268	383+75	0.3[b]	0.0
2.348	124+00	0.9	2.2	7.670	405+00	-0.2[b]	0.0
2.760	145+75	1.7	1.1	9.626	508+25	0.6[c]	0.2

---

a. Deposition values are for the period April 2002 to March 2007, except as noted.
b. 6-Year Period (2001-2007)
c. 21-Year Period (1980 to 2001)

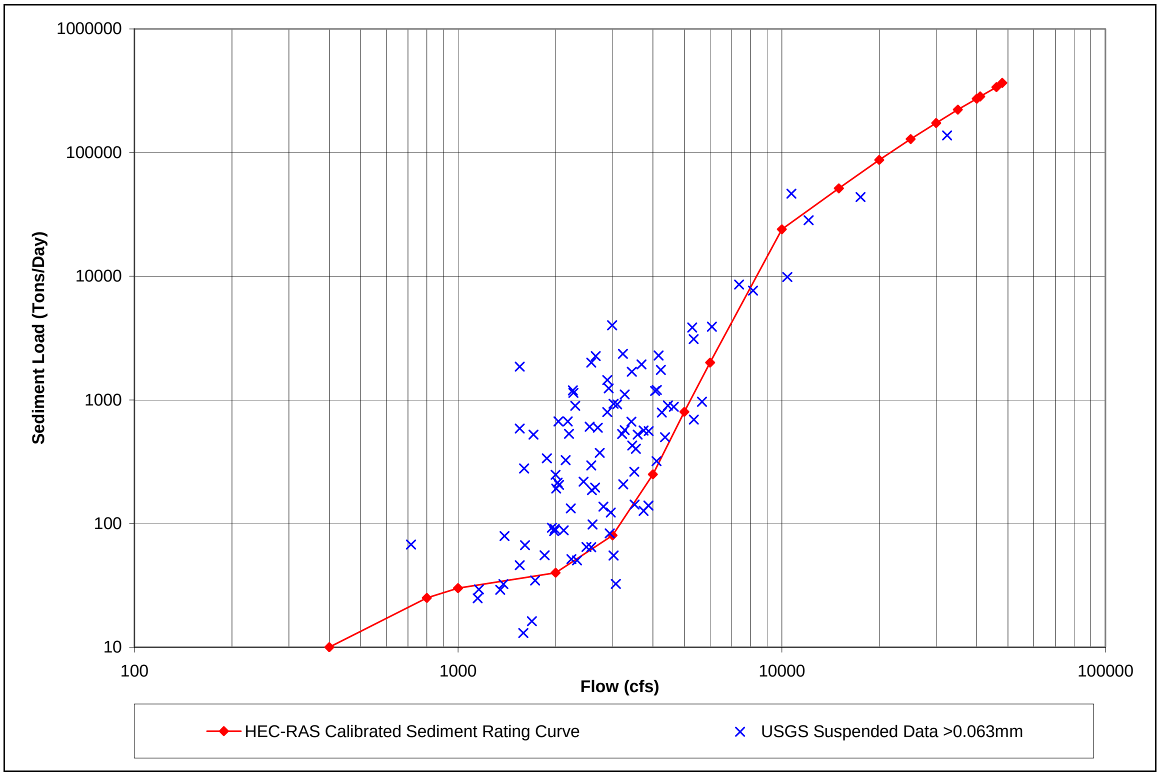

Figure 4-9. Sediment Inflow Rating Curve With USGS Suspended Sediment Data

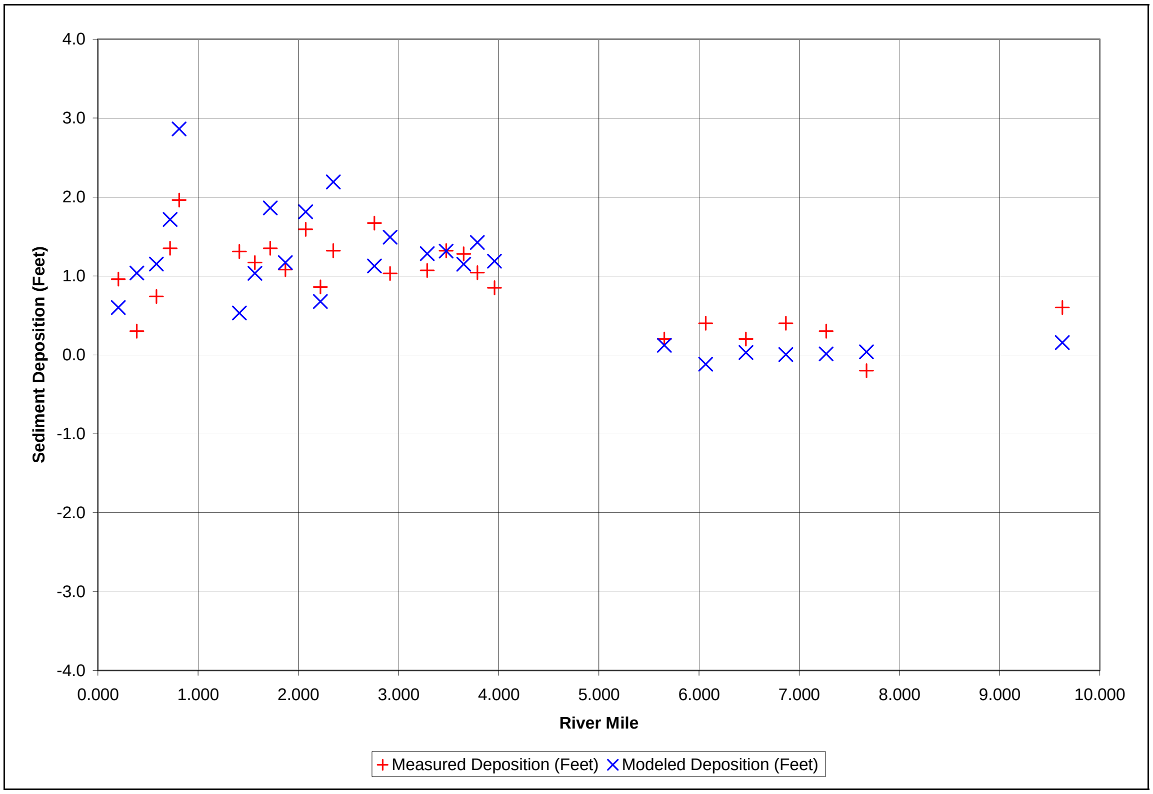

Figure 4-10. Comparison of Measured Deposition to Modeled Deposition

The total volume of sediment deposited in the modeled reach between March 2002 and April 2007 was calculated by multiplying the average change in elevation at each modeled cross-section by the cross-section width and length between adjacent cross-sections. This volume was then converted to a mass, assuming a bulk unit weight of 95 pounds per cubic foot. For the river reach between Commencement Bay and RM 3.65, which is the entire reach for which sediment deposition has been observed from the field surveys, the model estimated a total sediment deposition of about 266,000 tons, compared to a measured total of about 238,000 tons. Overall, the model agrees well with the survey data: computed sediment deposition is 12 percent higher than the measured sediment deposition.

MODEL APPLICATION

The following sections describe the application of the adjusted HEC-RAS 4.0 model to identify locations and characteristics of sediment deposits that affect flood profile elevations over the next 50 years in the Lower Puyallup River.

Accumulated Load Curves

A useful way to assess the sedimentation dynamics of a stream is to plot the “total accumulated load” of sediment as a function of stream distance. The total accumulated load is the total mass (or weight) of sediment that passes a given section of the river for the total time period of the analysis. A reduction in total accumulated load in the downstream direction indicates sediment deposition in the reach as the total transported load decreases; the deposition results in channel aggradation. Conversely, an increase in total accumulated load in the downstream direction indicates sediment erosion in the reach as the total transported load increases; the erosion results in channel incision. The total accumulated load on the modeled reach of the Puyallup River for 10-, 20-, 30-, 40- and 50-year simulation periods is shown in Figures 4-11 through 4-15, respectively.

The computed total load is fairly horizontal from the upper end of the study reach downstream to approximately RM 5, indicating that sediment passes through this upper reach without significant erosion or deposition of sands in the bed material. This is consistent with the small amounts of sediment deposition observed from the field measurements upstream of RM 5. Near RM 5, the bed slope of the Puyallup River flattens from approximately 0.0006 feet/foot upstream to a downstream slope of 0.0003 feet/foot. The decrease in slope lowers the sediment capacity (Hydrologic Engineering Center, 1993) and promotes deposition. This is evident in the model results, which show the accumulated load curve decreasing downstream of RM 5. The computed deposition below RM 5 is also consistent with observations of significant deposition as measured through channel cross-section surveys on the lowermost reach of the Puyallup River.

Comparison of Figures 4-11 through 4-15 show that the modeled “trap efficiency” (the percentage of sediment inflow that is deposited in the study reach) decreases over time. Over the initial 10 years of simulation, approximately 13 percent of all bed material sediment transported into the modeled reach remains in the channel as deposition; whereas over the last 10 years of simulation time, less than 5 percent of bed material sediment transported into the reach remains as deposition. This trend suggests that without any major changes to the bed configuration (i.e. dredging) the long-term deposition in the reach will eventually become nearly equivalent to the long-term erosion. This quasi-equilibrium state is the result of the raised bed elevation (and hence increased stream slope) caused by sediment deposition in the river channel, tidally constrained water surface elevations, and tidal current and wave erosion of sediment deposited on the Commencement Bay sand flats (see Appendix D for a comparison of sand flat morphology) combining to produce increased velocities in the reach. This increased slope and flow velocity increases the sediment capacity of the reach, reducing the propensity of deposition in the lower Puyallup River.

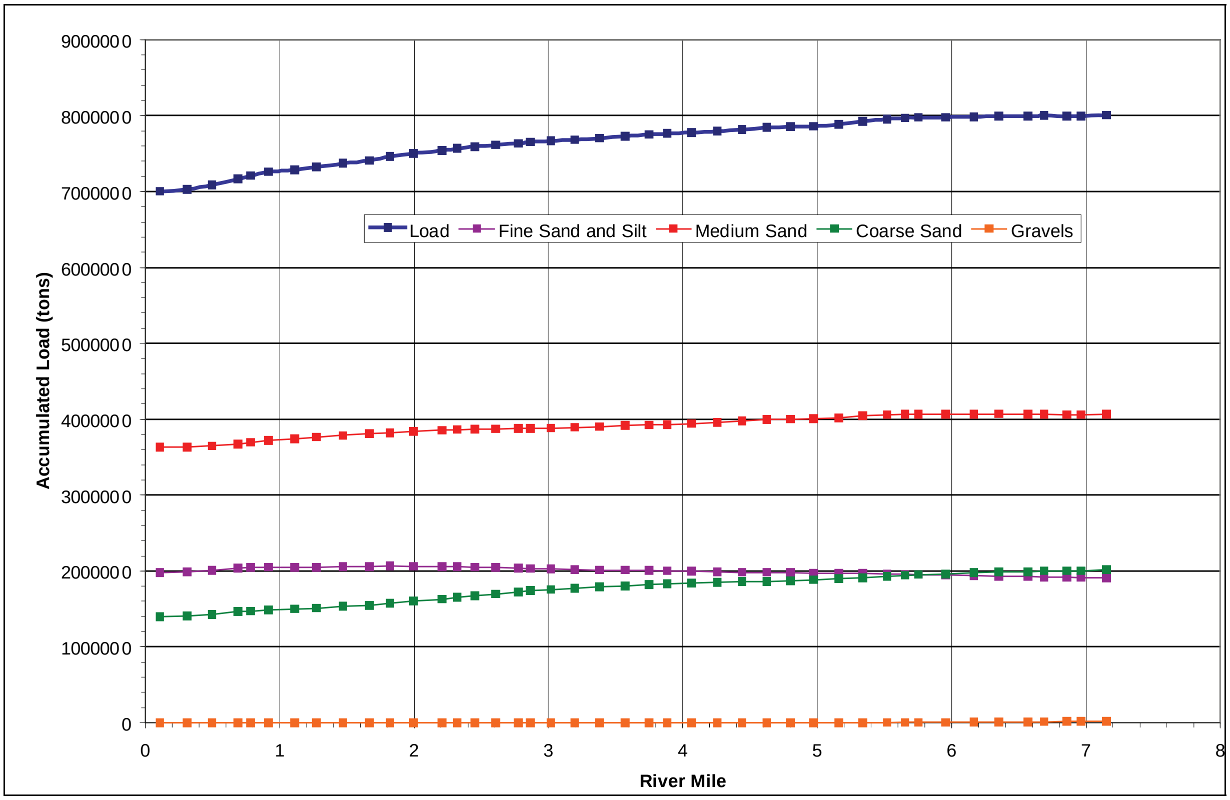

Figure 4-11. Total Accumulated Load Over 10 Years of Simulation

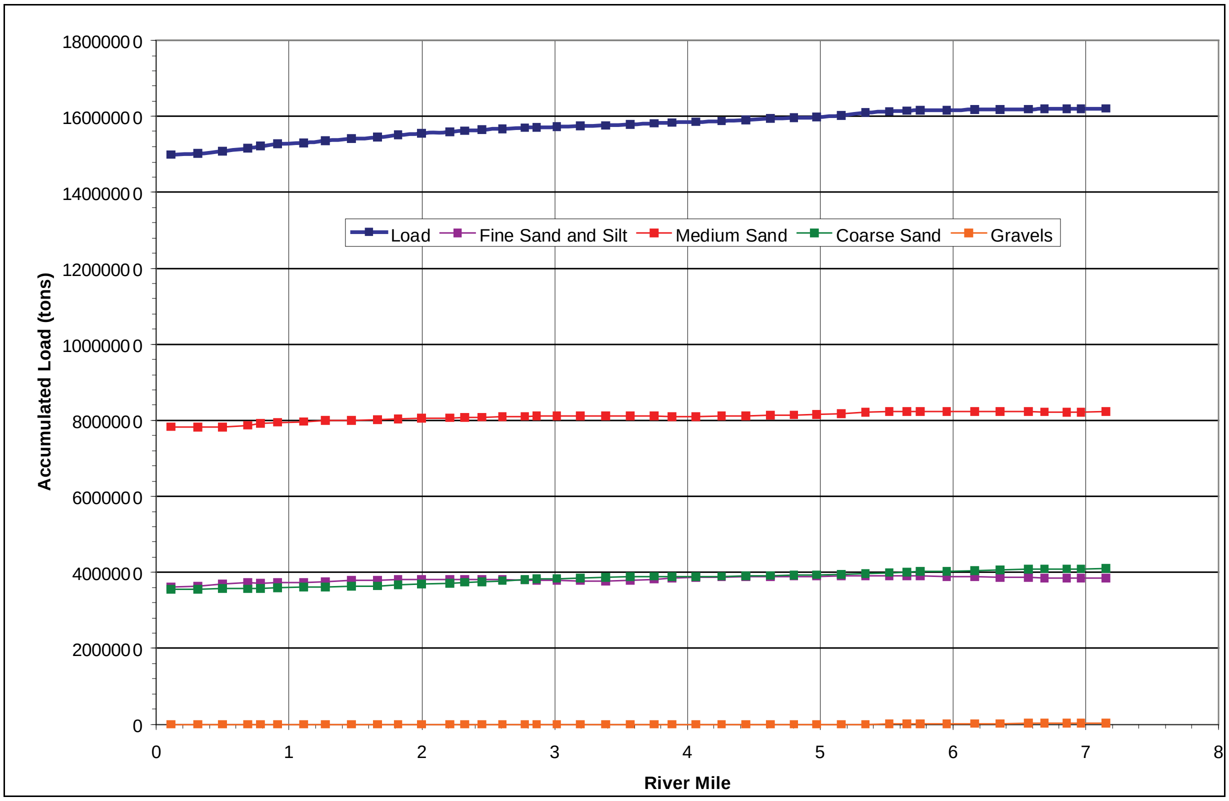

Figure 4-12. Total Accumulated Load Over 20 Years of Simulation

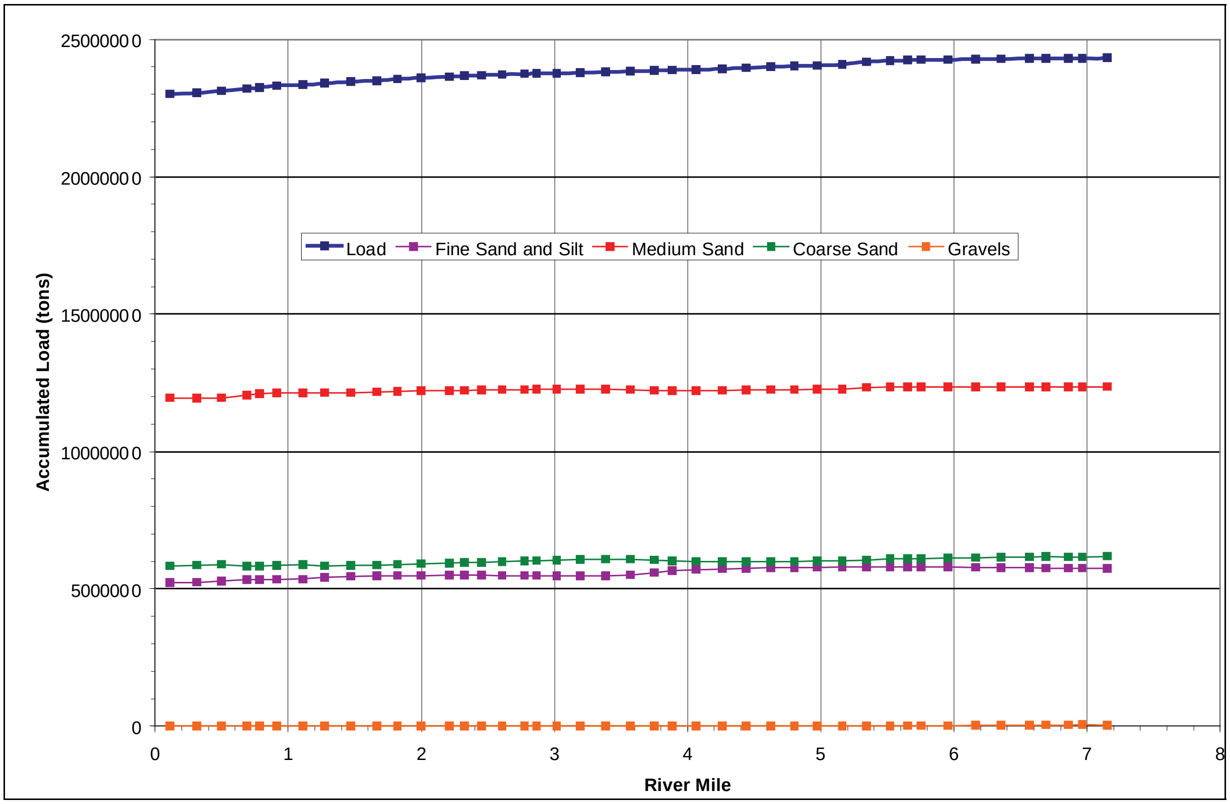

Figure 4-13. Total Accumulated Load Over 30 Years of Simulation

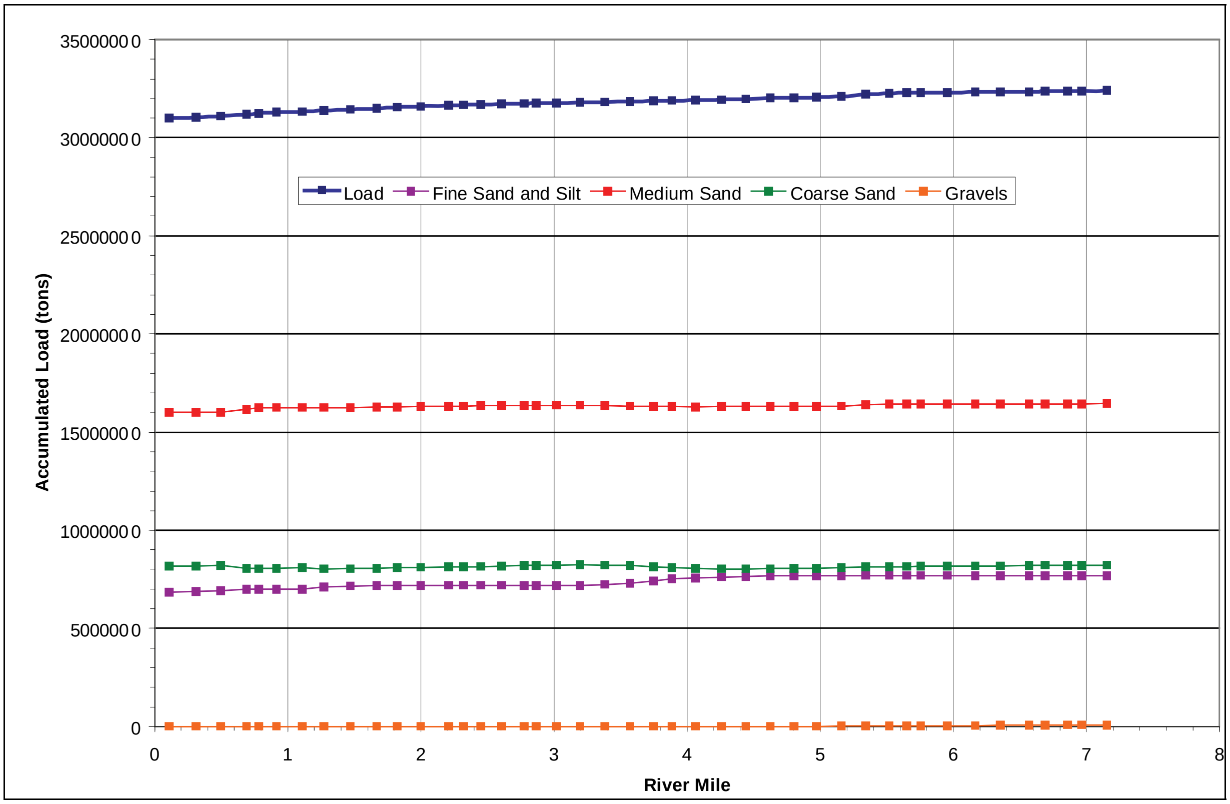

Figure 4-14. Total Accumulated Load Over 40 Years of Simulation

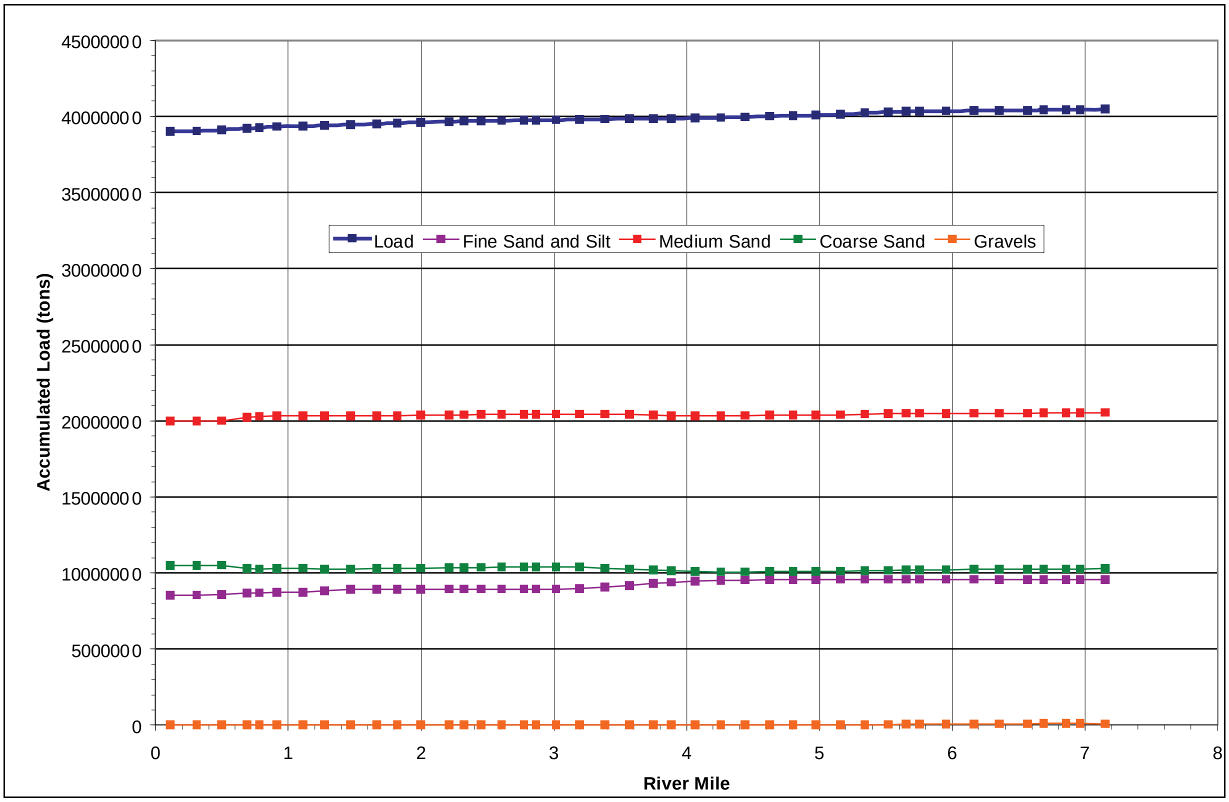

Figure 4-15. Total Accumulated Load Over 50 Years of Simulation

Figures 4-11 through 4-15 also include the load composition throughout the reach. The transported sediment is primarily sands, with trace amounts of gravel. Although it is not apparent in these figures due to the high magnitudes of sand being transported, most gravel is deposited along gravel bars near RM 5, with only trace quantities being transported beyond this point. This is consistent with bed material sampling that found no appreciable amounts of gravel in the lower reach. During the first two decades of simulation, the deposition in the downstream portion of the modeled reach is primarily composed of coarse sands. This is evident in Figures 4-11 and 4-12, in which the amount of coarse sand in the load decreases, following a slope similar to that of the total load. During the final three decades of the simulation, the composition of the load remains fairly constant throughout all of the cross-sections, suggesting that equal amounts of each inflowing grain size are being deposited.

Table 4-2 provides an estimate of the average change in bed elevation that could be expected to occur in a cross-section as a result of sediment erosion (-) or deposition (+).

TABLE 4-2.
BED ELEVATION CHANGE SUMMARY

River Mile	Average Change in Bed Elevation (feet)				
	10 Years	20 Years	30 Years	40 Years	50 Years
0.1098	0.7	0.7	0.9	0.9	0.9
0.3116	1.6	1.8	2.1	2.1	2.2
0.4989	2.2	2.2	2.2	2.3	2.4
0.6909	1.2	1.3	1.4	1.4	1.7
0.7837	3.6	4.6	5.0	5.1	5.0
0.9159	1.5	1.6	1.7	1.7	1.7
1.1107	1.6	2.3	2.3	2.3	2.0
1.2739	2.5	2.6	2.6	2.6	2.3
1.4719	1.6	1.8	1.9	2.3	2.4
1.6676	2.3	2.6	2.6	2.6	2.5
1.8213	2.7	3.0	3.0	3.1	2.9
1.9991	2.1	2.2	2.1	2.2	2.1
2.2095	1.6	1.7	1.7	1.8	1.6
2.322	2.3	2.5	2.4	2.3	2.1
2.4528	2.1	2.3	2.3	2.3	2.1
2.6079	1.7	1.7	1.7	1.6	1.5
2.7758	1.2	1.2	1.1	1.2	1.1
2.8659	1.7	1.8	1.8	2.1	2.0
3.0173	1.6	1.5	1.5	1.6	1.6
3.1956	1.1	0.9	1.0	1.5	1.8
3.384	1.8	1.8	2.0	2.0	1.0
3.5709	1.4	2.0	2.0	1.9	1.3
3.7498	0.8	1.0	1.2	1.4	-0.1
3.8858	1.1	1.4	1.3	0.8	2.9
4.0646	1.0	1.4	1.6	1.6	1.3
4.2584	1.3	1.9	2.2	2.2	3.1
4.4416	1.5	2.1	2.0	2.8	3.3
4.6266	0.6	1.1	1.5	1.6	1.8
4.8027	0.4	1.2	1.4	1.3	1.9
4.9728	1.3	2.7	2.6	2.6	2.8
5.1614	2.1	3.3	4.7	5.1	5.2
5.3422	1.4	1.9	2.1	2.9	3.1
5.5215	1.0	1.2	1.5	2.0	2.6
5.6532	0.7	0.9	0.9	0.8	1.2
5.7554	0.1	0.2	0.4	0.4	0.5
5.9554	0.5	0.6	0.7	0.7	1.2
6.1661	0.4	0.5	0.7	0.8	1.2
6.3531	0.1	0.3	0.4	0.4	0.7
6.5693	0.2	0.3	0.5	0.9	1.1
6.6898	-0.4	-0.1	-0.2	0.2	0.6
6.8592	-0.1	0.0	0.1	0.1	0.4
6.9646	1.4	1.9	2.9	3.2	3.0
7.154	0.5	0.6	0.6	0.9	1.5

The change in bed elevation is calculated as a function of the total mass of sediment eroded or deposited in the simulation at each cross-section. The erosion or deposition is assumed to occur uniformly between the stream banks. Although it is not likely that the cross-sectional shape will stay constant over time, the assumptions of one-dimensional sediment transport modeling are best presented as average bed elevation changes. Localized scour or depositions may result in thalweg adjustment or bank-line deposition that may skew the net distribution of bed material deposition over the long term. However, this approach provides a reasonable approach for quantifying the expected average sediment accumulation at each cross-section over the multi-decade simulation period.

Effect of Sedimentation on Flood Levels

Specific gage plots show predicted flood elevations over time, providing a means to assess the effects of sedimentation on flood elevation. Specific gage plots for several locations along the Puyallup River were developed for flows of 5,000 cfs, 10,000 cfs, 20,000 cfs, 40,000 cfs and 50,000 cfs. Figures 4-16 through 4-20 show these plots for locations at about 2-mile increments throughout the modeled reach. In the lowermost reaches downstream of the I-5 bridge (Figures 4-16 and 4-17), water surface elevations would increase 3 to 4 feet over the 50-year simulation period. Further upstream, the changes are less. Water surface elevations increase 2 to 3 feet near the Clark Street bridge (Figure 4-18), and less than 3 feet near the USGS Puyallup River Gage (Figure 4-19) and the Milwaukee Street bridge (Figure 4-20). In the lowermost reaches, the increase in the water surface elevations occurs primarily over the first 10 years.

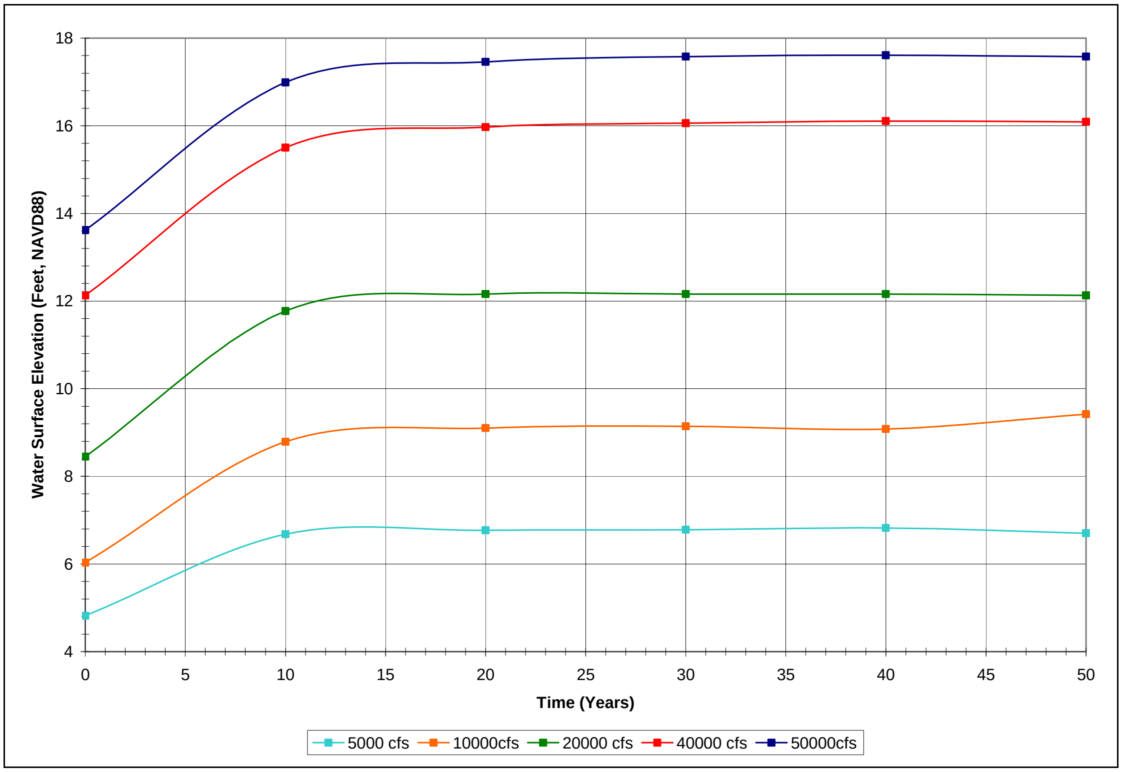

Figure 4-16. Specific Gage Analysis at River Mile 1.4719

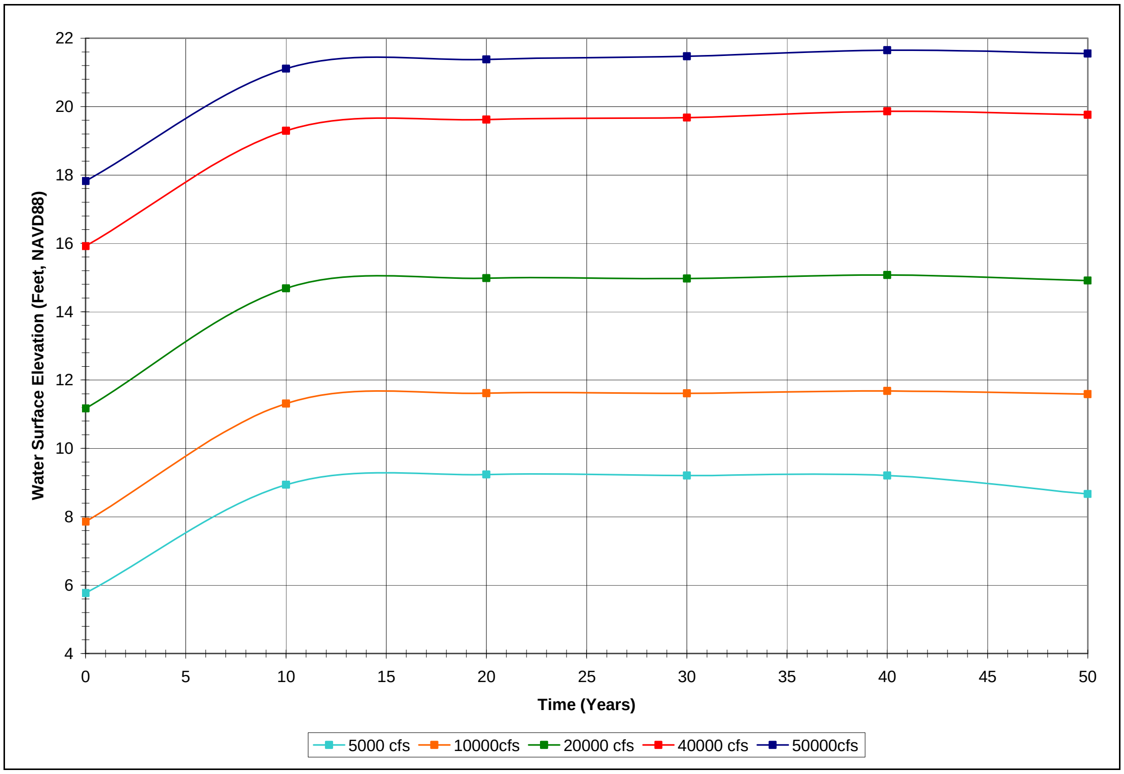

Figure 4-17. Specific Gage Analysis at River Mile 2.322

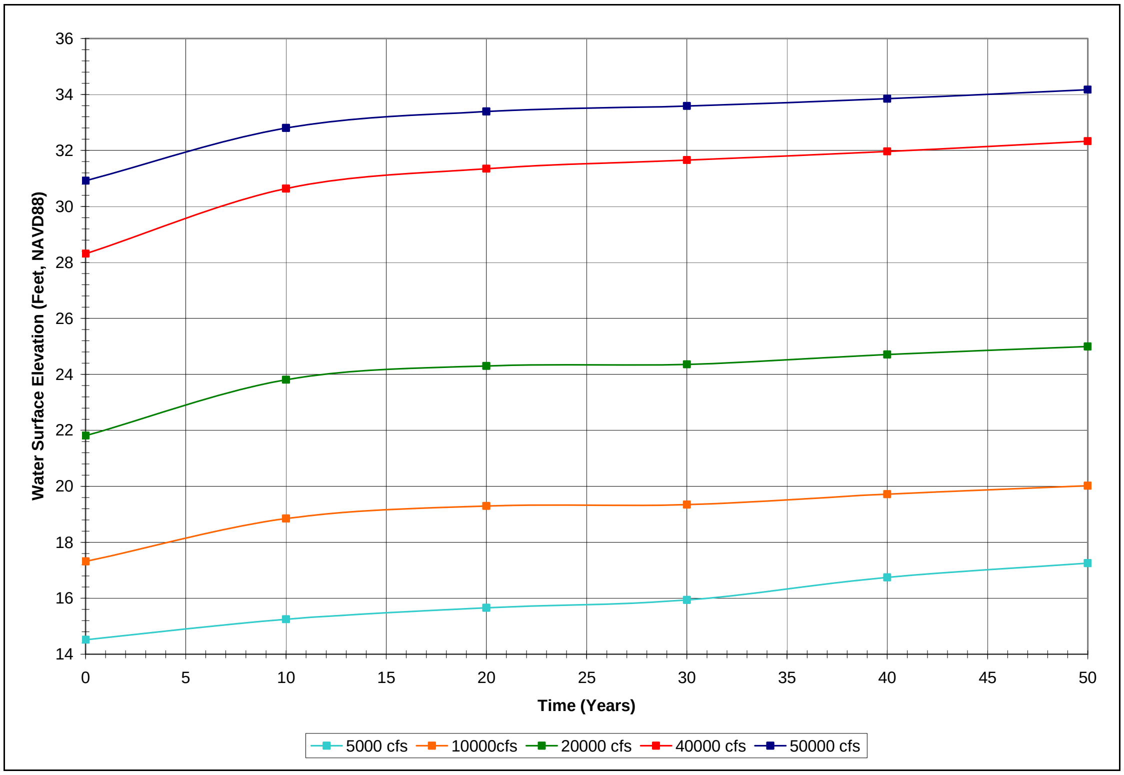

Figure 4-18. Specific Gage Analysis at River Mile 5.7554

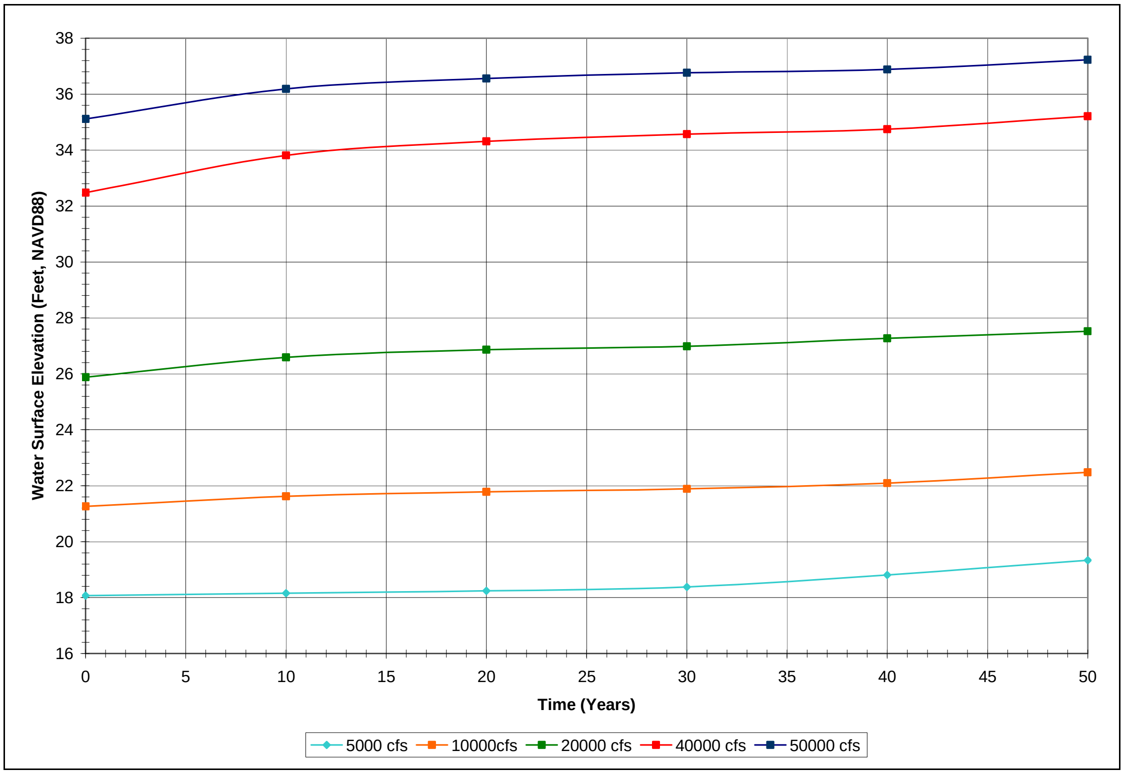

Figure 4-19. Specific Gage Analysis at River Mile 6.5693

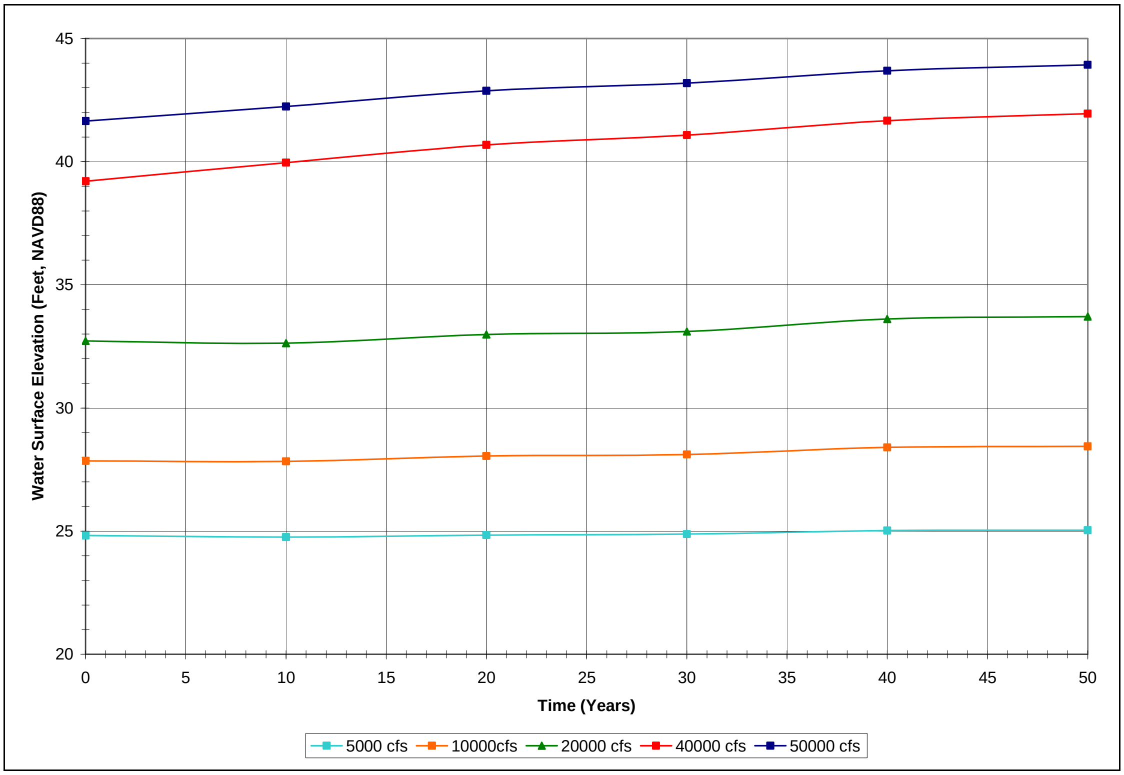

Figure 4-20. Specific Gage Analysis at River Mile 8.669

Table 4-3 shows 100- and 500-year flood elevations for the predicted sediment levels in 2007, 2017 and 2057 at 64 locations along the Lower Puyallup. The elevations listed in this table assume that all the river flow stays in the river channel. In reality, overtopping of levees at some locations would release water to the floodplain. This would cause water surface elevations downstream of the overtopping location to be lower than those presented in the table. The table shows that the 100-year flood elevation would be as much as 2.0 feet higher in 2057 than in 2007 (at RM 2.2682, RM 2.4032, RM 2.4528 and RM 4.0646); the 500-year flood elevation would be as much as 2.2 feet higher in 2057 than in 2007 (at RM 2.4032).

SUMMARY OF SEDIMENTATION MODELING ANALYSIS

The sediment transport modeling predicts increases in bed elevation over a 50-year time period throughout the study reach; the increases would be greatest in the lower end of the study reach. A detailed statistical analysis of the hydrologic and sediment data used in the model was not performed, but no obvious trends in peak discharge magnitude or flow duration are evident in the data. Therefore the rates and locations of aggradation and subsequent increases in flood elevation profile over the next 50 years are considered to be reasonably presented by this analysis.

The analysis indicates that the Puyallup River is tending toward a state of quasi-equilibrium. The accumulated load curves show a trend of decreasing trap efficiency in the study reach. As the trap efficiency approaches zero, the downstream reach would achieve a steady state condition with nearly equivalent amounts of sediment leaving and entering the system over a period of time. The specific gage plots shows an overall increase in peak flood water surface elevations during the first 10 years of simulation and a much smaller increase for the remainder of the 50-year simulation. The time needed for the system to reach a quasi-equilibrium state will depend on actual flow events and sediment loading.

The primary controls on the reduction of trap efficiency and sediment deposition rate over time are the bed and water surface elevation in the Puyallup River delta at Commencement Bay. Although the size of the delta appears to be significant from aerial photos, this tidal sand flat is worked by currents resulting from diurnal tides with a range of about 10 feet, and by wind waves during periods of inundation and high winds, which are not uncommon in Puget Sound. Commencement Bay beyond the limits of the delta is a significant sink for additional sediment deposition; adjacent depths of the bay are on the order of 100 feet or more and worked by the relatively strong tidal currents. Transects were surveyed over the sand flat delta surface in 1997, and a bathymetric survey of the same area was completed by the Corps of Engineers in 2001. The 2007 survey transects and those cut from the 2001 bathymetric survey are provided in Appendix E. These transects indicate that both erosion and deposition have occurred over this time period, but the average elevation of the delta is approximately equivalent between the two surveys.

TABLE 4-3.
PREDICTED FLOOD ELEVATIONS AT 2007, 2017 AND 2057 BED LEVELS

River Mile	100-Year Flood Elevation (feet) 2007	100-Year Flood Elevation (feet) 2017	100-Year Flood Elevation (feet) 2057	500-Year Flood Elevation (feet) 2007	500-Year Flood Elevation (feet) 2017	500-Year Flood Elevation (feet) 2057
0.1098	9.2	9.2	9.2	9.2	9.2	9.2
0.3116	9.6	9.6	9.6	9.7	9.8	9.7
0.4989	10	10.1	10	10.3	10.3	10.3
0.6909	10.6	10.7	10.7	10.9	11.1	11.1
0.7	11th Street Bridge					
0.7286	10.7	10.8	10.9	11.2	11.4	11.5
0.7837	11.2	11.3	11.4	11.8	12	12.1
0.8292	11.6	11.8	11.9	12.3	12.5	12.6
0.9159	11.8	12	12.1	12.4	12.7	12.8
1.1107	12.7	12.9	12.9	13.5	13.6	13.7
1.2739	13.4	13.9	13.9	14.2	14.7	14.8
1.4366	14	14.4	14.5	14.9	15.2	15.3
1.45	Lincoln Avenue Bridge					
1.4719	14.4	14.8	14.9	15.3	15.7	15.8
1.5172	14.5	14.8	14.9	15.4	15.7	15.8
1.6676	15.1	15.6	15.6	16.1	16.5	16.6
1.8213	15.7	16.2	16.2	16.7	17.1	17.2
1.9716	16.2	17	17.1	17.2	18	18.2
1.98	BNSF Railway Bridge					
1.9991	16.5	16.9	17.3	17.5	18	18.4
2.0417	16.7	17.2	17.5	17.8	18.2	18.6
2.08	Eells Street (Old Highway 99) Bridge					
2.122	17	18.4	18.5	18.1	19.6	19.6
2.1759	17.5	19	18.9	18.6	20.1	20.1
2.2095	17.4	18.9	18.9	18.6	20.1	20
2.23	TRMD Railroad Bridge					
2.2682	17.8	19.7	19.8	19	21	21
2.322	18.4	20.3	20.3	19.7	21.5	21.6
2.37	Interstate 5 Bridge					
2.4032	19.3	21.2	21.3	20.7	22.6	22.9
2.4528	19.5	21.4	21.5	20.9	22.8	22.9
2.4817	19.6	21.4	21.5	20.9	22.8	22.9
2.53	Union Pacific Railroad Bridge					
2.6079	20.5	22.1	22.3	21.9	23.6	23.8
2.7758	21.4	22.8	23	22.9	24.3	24.5
2.8659	21.9	23	23.2	23.4	24.6	24.7
3.0173	22.4	23.7	23.8	23.9	25.1	25.3
3.1956	23.2	24.5	24.8	24.6	25.9	26.2
3.384	23.9	25.2	25.5	25.4	26.7	26.9
3.5709	24.5	25.9	26.3	26	27.3	27.7
3.7498	25.1	26.5	27	26.7	28	28.4
3.8858	25.8	27.2	27.7	27.4	28.6	29.1
4.0646	26.3	27.8	28.3	28	29.2	29.7
4.2584	26.9	28.3	28.8	28.6	29.8	30.2
4.4416	27.5	28.9	29.3	29.2	30.3	30.8
4.6266	27.8	29.1	29.6	29.5	30.6	31
4.8027	28.3	29.5	30	30	31	31.4
4.9728	28.8	29.9	30.4	30.5	31.4	31.9
5.1614	29.5	30.5	30.9	31.2	32	32.4
5.3422	29.7	30.7	31.1	31.4	32.2	32.6
5.5215	30	30.9	31.3	31.7	32.5	32.8
5.6532	30.2	31.1	31.4	31.8	32.6	32.9
5.7043	30.3	31.1	31.5	31.9	32.6	33
5.71	66th Avenue East/Clark Street Bridge					
5.7208	30.3	31.1	31.4	31.9	32.6	33
5.7554	30.6	31.4	31.7	32.2	32.9	33.3
5.9554	31.5	32.2	32.5	33.2	33.8	34.1
6.1661	32.1	32.7	32.9	33.7	34.2	34.6
6.3531	33	33.5	33.7	34.6	35.1	35.4
6.5182[b]	33.7	34.1	34.3	35.3	35.8	36
6.5693	33.9	34.3	34.5	35.6	36	36.2
6.6898	34.5	34.9	35	36.2	36.6	36.8
6.8592	35.3	35.6	35.8	37	37.4	37.5
6.9646	35.5	35.8	36	37.2	37.5	37.7
7.1817	36.4	36.6	36.7	38	38.3	38.4
7.3707	37.1	37.3	37.4	38.8	39.1	39.2
7.5619	37.6	37.8	37.9	39.2	39.5	39.6
7.7803	38.9	39.1	39.2	40.6	40.7	40.8
7.9331	39.4	39.5	39.6	41.1	41.2	41.3
8.1316	40.2	40.3	40.3	41.9	42	42.1
8.136	SR-167/Meridian Street Bridge					
8.149	40.4	40.5	40.6	42.2	42.4	42.4
8.1719	40.3	40.4	40.5	42.1	42.2	42.3

---

a. USGS Gage Puyallup at Puyallup is located at Station 6.5182