RECLAMATION

Managing Water in the West

Sediment Transport Modeling of the Yakima Basin

A component of
Yakima River Basin Water Storage Feasibility Study, Washington

Technical Series No. TS-YSS-17

U.S. Department of the Interior
Bureau of Reclamation
Technical Service Center
Denver, Colorado

January 2008

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PREFACE

The Congress directed the Secretary of the Interior, acting through the Bureau of Reclamation, to conduct a feasibility study of options for additional water storage in the Yakima River basin. Section 214 of the Act of February 20, 2003 (Public Law 108-7), contains this authorization and includes the provision "… with emphasis on the feasibility of storage of Columbia River water in the potential Black Rock Reservoir and the benefit of additional storage to endangered and threatened fish, irrigated agriculture, and municipal water supply."

Reclamation initiated the Yakima River Basin Water Storage Feasibility Study (Storage Study) in May 2003. As guided by the authorization, the purpose of the Storage Study is to identify and examine the viability and acceptability of alternate projects by: (1) diversion of Columbia River water to a potential Black Rock reservoir for further water transfer to irrigation entities in the lower Yakima River basin as an exchange supply, thereby reducing irrigation demand on Yakima River water and improving Yakima Project stored water supplies; and (2) creation of additional water storage within the Yakima River basin. In considering the benefits to be achieved, study objectives are to modify Yakima Project flow management operations to improve the flow regime of the Yakima River system for fisheries, provide a more reliable supply for existing proratable water users, and provide water supply for future municipal demands.

State support for the Storage Study was provided in the 2003 Legislative session. The 2003 budget included appropriations for the Washington State Department of Ecology (Ecology) with the provision that the funds ". . . are provided solely for expenditure under a contract between the department of ecology and the United States bureau of reclamation for the development of plans, engineering, and financing reports and other preconstruction activities associated with the development of water storage projects in the Yakima river basin, consistent with the Yakima river basin water enhancement project, P.L. 103-434. The initial water storage feasibility study shall be for the Black Rock reservoir project." Since that initial legislation, the State of Washington has appropriated additional matching funds.

Storage Study alternatives were identified from previous studies by other entities and Reclamation, appraisal assessments by Reclamation in 2003 through 2006, and public input. Reclamation filed a Notice of Intent and Ecology filed a Determination of Significance to prepare a combined Planning Report and Environmental Impact Statement (PR/EIS) on December 29, 2006. A scoping process, including two public scoping meetings in January 2007 identified several concepts to be considered in the Draft PR/EIS. Those concepts have been developed into “Joint” and “State” Alternatives.

The Joint Alternatives fall under the congressional authorization and the analyses are being cost-shared by Reclamation and Ecology. The State Alternatives are outside the congressional authorization, but within the authority of the state legislation, and will be analyzed by Ecology only. Analysis of all alternatives will be included in the Draft PR/EIS.

This technical document and others explain the analyses performed to determine how well the alternatives meet the goals of the Storage Study and the impacts of the alternatives on the environment. These documents will address such issues as hydrologic modeling, sediment modeling, temperature modeling, fish habitat modeling, and designs and costs. All technical documents will be referenced in the Draft PR/EIS and available for review.

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INTRODUCTION

Reclamation's Technical Service Center (TSC) was asked to perform a sediment transport analysis for selected reaches of the Yakima and Naches Rivers. This effort is in support of the Yakima River Basin Water Storage Feasibility Study and provides information on substrate, redd scour, and sand deposition for the Ecosystems Diagnostic Treatment (EDT) model and a Decision Support System (DSS) by the United States Geological Survey (USGS). Sediment Impact Analysis Methods (SIAM) was selected to provide average annual sediment loads. Sediment loads were used to derive the following EDT parameters:

- Gravel Transport: estimated average annual load for gravel and larger size materials.

- Redd Scour: estimated average annual depth of bed material disturbance due to sediment transport.

- Embeddedness: estimated average annual transport potential of sand particles (2 mm - 0.0625mm).

Parameters for the DSS included:

- Incipient Motion Threshold: critical discharge required for initiation of motion over the majority of the bed. The DSS sums the number of days where motion occurs.

- Flushing Flow: transport potential of fine materials for representative flow rates. The DSS reports the annual potential mass of fine materials the river can move.

- Geomorphic Work: daily energy expended in performing geomorphic work (sediment transport). The DSS reports the sum of the 10-day maximum work.

- Redd Scour: depth of bed material disturbance (active layer thickness) for representative flow rates due to sediment transport. The DSS reports number of flows greater than a user-defined depth.

The sediment analysis parameters make several assumptions without calibration to field measurements. Therefore, these parameters represent surrogates of physical processes rather than concrete estimates. The relative change between scenarios is likely accurate, but the absolute value is subject to significant levels of uncertainty.

Figure 1 shows the general reaches with sufficient hydraulic and bed material data to perform sediment transport calculations. Appendix A shows the breakdown into EDT Reaches. Due to insufficient channel bed surveys, results from a few reaches of the study are not included. Those reaches include Yakima R-7 and R-8 and Naches R-1. Refer to Hilldale and Mooney (2007) for more information about the insufficient surveys.

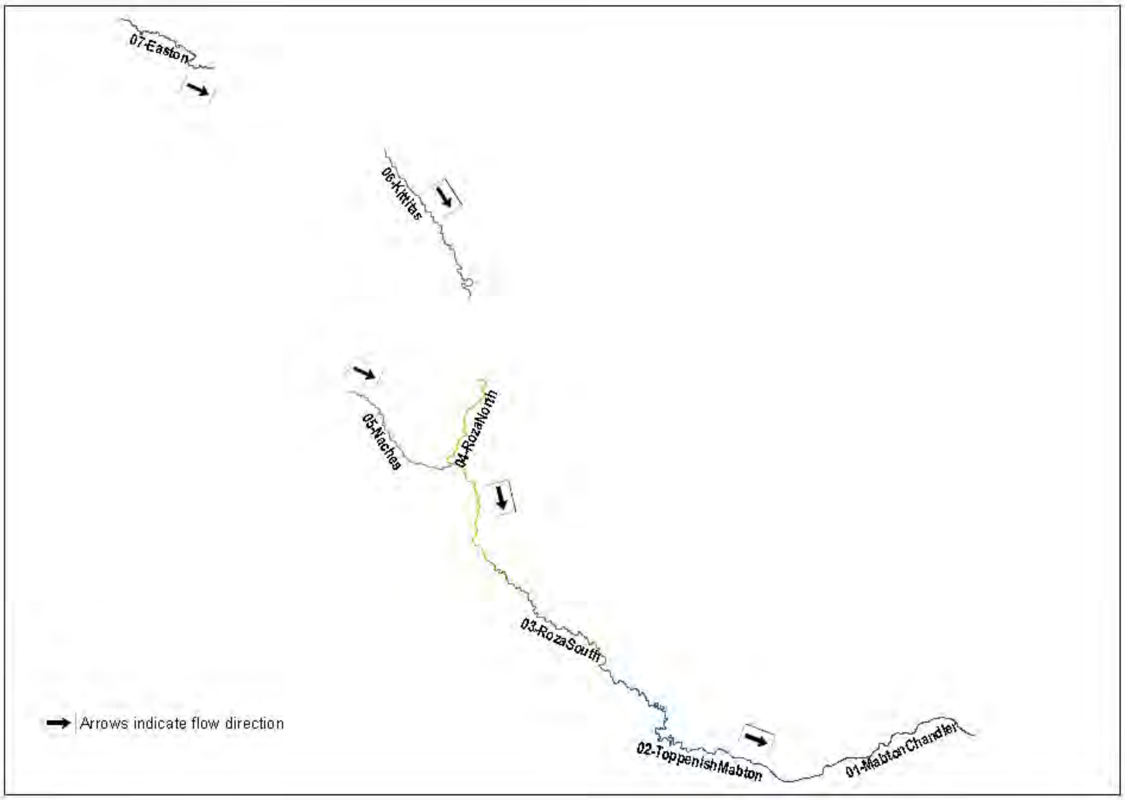

Figure 1. Yakima River study reaches

The following discussion covers the methods used to determine sediment transport, the uncertainty in the results, applicability, and limitations. Analysis included the following flow scenarios:

- Current
- No Action
- Black Rock 1
- Black Rock 2

- Wymer 1
- Wymer 2
- Wymer Plus

The Mobrand website, www.mobrand.com/edt, describes the features of each scenario and the differences. An electronic data appendix provides results and intermediate steps. Table 1 shows the reaches considered for analysis.

Table 1. EDT reach breakdown

ReachName	Description
Yakima R.-1A	Yakima R: Yakima Delta (RM 0 to 2.1).
Yakima R.-1B	Yakima R: Delta to Horn Dam (RM 2.1 to 18).
Yakima R.-1C (Horn Rapids Dam)	Yakima R: Horn Dam (RM 18.0)
Yakima R.-1D	Yakima R: Horn Dam to Benton Bridge (RM 18 to 29.8).
Yakima R.-1E	Yakima R: Benton Bridge to Corral Canyon Cr. (RM 29.8 to 33.5).
Yakima R.-1F	Yakima R: Corral Canyon Cr. to Prosser Powerplant Outfall (RM 33.5 to 35.8)
Yakima R.-2	Yakima R: Chandler Powerplant Outfall to Snipes Cr. (RM 35.8 to 41.8).
Yakima R.-2A	Yakima R: Snipes Cr. to Prosser Acclimation Site (RM 41.8 to 47.1).
Yakima R.-2B2 (Prosser Dam and Hatchery)	Yakima R: Prosser Dam (RM 47.1)
Yakima R.-2C	Yakima R: Prosser Dam to Mabton (RM 47.1 to 55).
Yakima R.-2D	Yakima R: Mabton to Sulpur Cr. Wasteway (RM 55 to 61)
Yakima R.-2E	Yakima R: Sulphur Cr. to Satus Cr. (RM 61 to 69.6).
Yakima R.-3	Yakima R: Satus Cr. to Toppenish Cr. (RM 69.6 to 80.4).
Yakima R.-4	Yakima R: Toppenish Cr. to Marion Drain (RM 80.4 to 82.6).
Yakima R.-4A	Yakima R: Marion Drain to Granger Drain (RM 82.6 to 83.2)
Yakima R.-5	Yakima R: Granger Drain to Sunnyside Dam (RM 83.2 to 103.8).
Yakima R.-5A (Sunnyside Dam)	Yakima R: Sunnyside Dam (RM 103.8).
Yakima R.-5B	Yakima R: Sunnyside Dam to Wapato Dam (RM 103.8 to 106.6).
Yakima R.-5C (Wapato Dam)	Yakima R: Wapato Dam (RM 106.6).
Yakima R.-5D	Yakima R: Wapato Dam to Ahtanum Cr. (RM 106.6 to 106.9).
Yakima R.-6	Yakima R: Yakima R., Ahtanum Cr. to Wide Hollow Cr. (RM 106.9 to 107.4)
Yakima R.-6A	Yakima R: Yakima R., Wide Hollow Cr. to Roza Powerplant Outfall (RM 107.4 to 113.3)
Yakima R.-6B	Yakima R: Yakima R., Roza Powerplant Outfall to Naches R. (RM 113.3 to 116.3)
Yakima R.-9A (Roza Dam)	Yakima R: Roza Dam (RM 127.9).
Yakima R.-9B	Yakima R: Roza Dam to Umtanum Cr. (RM 127.9 to 139.8).
Yakima R.-10	Yakima R: Umtanum Cr. to Wilson Cr. (RM 139.8 to 147).
Yakima R.-11	Yakima R: Wilson Cr. to Bull Ditch outtake (RM 147 to 153.5).
Yakima R.-11A	Yakima R: Bull Ditch outtake to Reecer Cr. (RM 153.5 to 153.7).

Yakima R.-11B	Yakima R: Reecer Cr. to Manastash Cr. (RM 153.7 to 154.5)
Yakima R.-11C	Yakima R: Manastash Cr. To Town Ditch Diversion Dam (RM 154.5 to 161.3
Yakima R.-11D (Town Ditch Diversion Dam)	Yakima R: Town Ditch Diversion Dam (RM 161.3)
Yakima R.-12	Yakima R: Town Ditch Diversion Dam to Taneum Cr. (RM 161.3 to 166.1).
Yakima R.-13	Yakima R: Taneum Cr. to Clark Flat Acclimation Site (RM 166.1 to 167.7).
Yakima R.-13A (Clark Flats Acclimation Site)	Yakima R: Clark Flats Acclimation Site (RM 167.7)
Yakima R.-13B	Yakima R: Clark Flats to Swauk Cr. (RM 167.7 to 169.9)
Yakima R.-14A	Yakima R: Swauk Cr to KRD 1146 drop structure (RM 169.9 to 172.9)
Yakima R.-14B	Yakima R: KRD 1176 drop structure to Teanaway R (RM 172.9 to 176.1)
Yakima R.-15	Yakima R: Teanaway R. to Cle Elum R. (RM 176.1 to 185.6).
Yakima R.-16	Yakima R: Cle Elum R. to Little Cr. (RM 185.6 to 194.6).
Yakima R.-17	Yakima R: Little Cr. to Big Cr. (RM 194.6 to 195.8).
Yakima R.-17A	Yakima R: Big Cr. to Tucker Cr. (RM 195.8 to 199.9)
Yakima R.-17B	Yakima R: Tucker Cr. To Easton Acclimation Site (RM 199.9 to 201.9)
Yakima R.-17C (Easton Acclimation Site)	Yakima R: Easton Acclimation Site (RM 201.9)
Yakima R.-18	Yakima R.: Easton Acclimation site to Easton Dam (RM 201.9 to 202.5)
Naches R.-2	Naches R: Cowiche Cr. to Buckskin Slough (RM 2.7 to 3.3)
Naches R.-3	Naches R: Buckskin Slough to Cowiche Dam (RM 3.3 to 3.6)
Naches R.-3A (Cowiche Dam)	Cowiche Dam (RM 3.6)
Naches R.-4	Naches R: Cowiche Dam to to S Naches Channel return (RM 3.6 to 9.8)
Naches R.-5	Naches R: S Naches Channel return to S Naches Channel diversion (RM 9.8 to 14.0)

METHODS

Sediment transport inputs included bed material, hydraulics, and hydrology. Grain size specific calculations divided material into log-2 phi scales, Table 2.

Table 2. Grain class divisions

Name	Phi	Mean Diameter (mm)	Fall Velocity (m/s)	Lower Diameter (mm)	Upper Diameter (mm)
Clay	-8.5	0.0028	3.40E-06	0.0020	0.0039
VFM	-7.5	0.0055	0.000014	0.0039	0.0078
FM	-6.5	0.0110	0.000055	0.0078	0.0156
MM	-5.5	0.0221	0.00022	0.0156	0.0313
CM	-4.5	0.0442	0.00088	0.03125	0.0625
VFS	-3.5	0.0884	0.00347	0.0625	0.125
FS	-2.5	0.177	0.0128	0.125	0.25
MS	-1.5	0.354	0.036	0.25	0.5
CS	-0.5	0.707	0.0703	0.5	1
VCS	0.5	1.414	0.112	1	2
VFG	1.5	2.828	0.167	2	4
FG	2.5	5.657	0.238	4	8
MG	3.5	11.31	0.338	8	16
CG	4.5	22.63	0.479	16	32
VCG	5.5	45.25	0.678	32	64
SC	6.5	90.51	0.959	64	128
LC	7.5	181.0	1.357	128	256
SB	8.5	362.0	1.919	256	512
MB	9.5	724.1	2.715	512	1024
LB	10.5	1448	3.839	1024	2048
VLB	11.5	2896	5.43	2048	4096

The transport calculations required selecting an applicable transport formula and calibrating transport parameters. SIAM uses reach average values. Reach selection began with the breakdown selected for EDT. Additional subreaches were created where hydraulic models indicated a significant change in width, depth, velocity, and slope. These are designated as SR1 and SR2 in the results.

Appendix B describes the collection of bed material samples along the Yakima and Naches Rivers and contains the complete records. Bed material samples provide the mass of material within each size class for surface and subsurface layers. Figure 2 shows the bed material gradations by river mile.

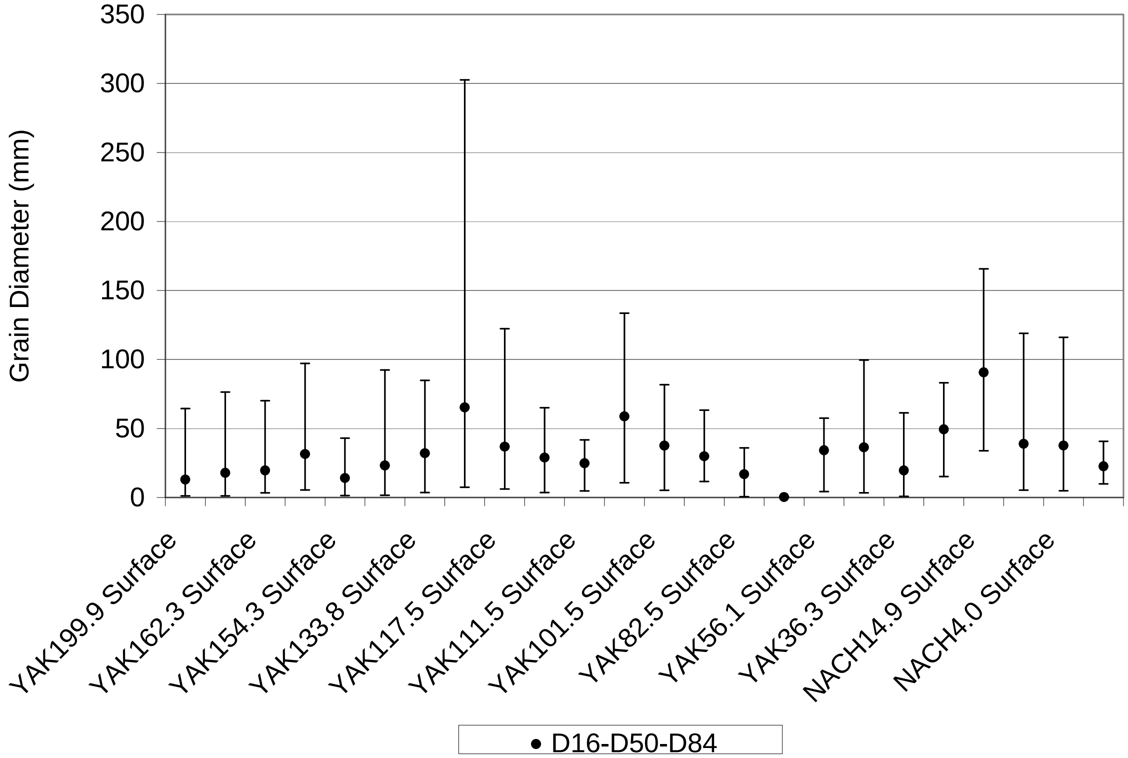

Figure 2. Yakima and Naches surface sample gradations

Hydrology determines the ranges of flows and durations experienced by the river over the simulation period. Results used mean daily flow data generated from simulation provided by Joel Hubble and Roger Sonnichsen (written comm., 2007). Appendix C describes hydrology processing for SIAM. An instantaneous time series was generated from the mean daily flows to capture storm peaks. A cumulative probability distribution function (CDF) was generated from the instantaneous series and then converted to a probability distribution function with 20 bins weighted to best represent high flows. Flows were annualized by multiplying the width of each bin by the number of days in a year to determine the average annual influence of each flow rate over the 20-year simulation period.

Hilldale and Mooney (2007) describe the development of the one-dimensional (1-D) hydraulic models. Results provide cross-section averaged water surface elevation and velocities. Reach-based hydraulics averaged all individual sections with a reach. Length-weighting was not applied due to the consistent cross-section spacing in the hydraulic models.

Sediment transport calculations used the Parker (1990) equation due to the strong link to physical processes and the wide application of the relationship, resulting in a good understanding of the performance. Parker (1990) contains two calibration parameters, hiding factor, and reference shear stress. The hiding factor controls the relative rates of transport within a gradation. No information was available to calibrate the hiding factor and no reasons were identified to alter the hiding factor from the values in the original equations. The reference shear stress controls the transport rate. No calibration information was available to set the reference shear stress; therefore, the slope-based equations of Mueller, Pitlick, and Nelson (2005), Equation 1, was applied.

$$\tau_* = 2.18 \cdot S + 0.021$$ **Equation 1**

Where,

τ_* = reference shear stress; and

S = slope of the channel.

The reference shear stress and hiding factors depend on the type of sediment sample. The analysis computed transport rates using surface gradations, sub-surface gradations, and combined surface and subsurface (average) gradations. Final results averaged the sediment load computed from each type of sediment sample. The gradation engaged in transport in the actuality will be a mix of surface and subsurface materials. There is no generally accepted method to estimate the mixing; therefore, the different techniques were averaged in order to provide some representation of the full range of gradations in transport. Table 3 shows the resulting surface sample reference shear stresses using the Mueller, Pitlick, and Nelson (2005) relationships, applicable to surface gradations only.

Table 3. Reference shear stresses for surface gradations (No Action Alternative)

Reach	Slope	Mueller et al Shear Stress
Yakima R.-18_sr2	0.00278	0.0271
Yakima R.-18_sr1	0.00216	0.0257
Yakima R.-17B	0.00314	0.0278
Yakima R.-17A	0.00219	0.0258
Yakima R.-17	0.00180	0.0249
Yakima R.-16	0.00209	0.0256
Yakima R.-11C	0.00245	0.0263
Yakima R.-11B	0.00216	0.0257
Yakima R.-11A	0.00364	0.0289
Yakima R.-11	0.00231	0.0260
Yakima R.-10	0.00160	0.0245
Naches R.-5	0.00539	0.0327
Naches R.-4	0.00524	0.0324
Naches R.-3_sr2	0.00488	0.0316
Naches R.-3_sr1	0.00454	0.0309
Naches R.-2	0.00469	0.0312

Yakima R.-6B	0.00300	0.0275
Yakima R.-6A_sr2	0.00246	0.0264
Yakima R.-6A_sr1	0.00251	0.0265
Yakima R.-6	0.00098	0.0231
Yakima R.-5D	0.00044	0.0220
Yakima R.-5B_sr2	0.00186	0.0250
Yakima R.-5B_sr1	0.00083	0.0228
Yakima R.-5	0.00151	0.0243
Yakima R.-4A	0.00071	0.0225
Yakima R.-4	0.00090	0.0230
Yakima R.-3_sr2	0.00078	0.0227
Yakima R.-3_sr1	0.00023	0.0215
Yakima R.-2E	0.00011	0.0212
Yakima R.-2D_sr2	0.00008	0.0212
Yakima R.-2D_sr1	0.00026	0.0216
Yakima R.-2C_sr2	0.00011	0.0212
Yakima R.-2C_sr1	0.00102	0.0232
Yakima R.-2A	0.00205	0.0255
Yakima R.-2	0.00182	0.0250
Yakima R.-1F	0.00111	0.0234
Yakima R.-1E	0.00077	0.0227

Subsurface and combined samples scaled the reference shear stress by the same amount as the ratio of the reported original surface values in Parker (1990) to Mueller, Pitlick and Nelson. Hiding factors remained constant. Table 4 shows the initial values before scaling.

Table 4. Initial reference shear stress values before scaling for sample types

Gradation	Original Reference Shear Stress	Hiding Factor
Surface	0.0386	0.9047
Sub-Surface	0.0876	0.982
Combined	0.07	0.94

Montgomery and Buffington (1997) surveyed reference shear stresses reported in literature under different conditions and provided ranges of variability. Sediment transport evaluations varied the reference shear stress plus and minus by 50 percent to test the sensitivity of results as well as applying the alternate relationships of Meyer-Peter and Muller (1948), Wilcock and Crowe (2003), and Wu, Wang, and Jia (2000).

Equations for sediment load measured the transport of material under hydraulically limiting conditions. Sand-sized grain classes are supply limited. The ability of the river to convey sand exceeds the amount of sand present in the bed. The transport potential measures the ability of a river to move material, assuming an infinite supply and no interference from other grain classes. Transport potential in sand classes provided a surrogate to evaluate the ability to maintain clean surface gravel. Transport potential for sand used the Engelund and Hansen relationship (1972). Yang (1972) provided a check.

Sediment transport rates were converted into estimates of depth by dividing by the unit weight of sediment, average top width of the active channel for the No Action Alternative, assuming a velocity of sediment transport, and ratios for the time spent in transport and the effective width of sediment movement.

$$y_s = \frac{Q_s}{\gamma_s \cdot W \cdot v_s \cdot R_w \cdot R_t} \qquad \textbf{Equation 2}$$

Where,

y_s = depth of scour;

Q_s = sediment load;

γ_s = unit weight of sediment;

W = top width of the active channel;

v_s = velocity of sediment;

R_w = ratio of width in motion to total top width; and

R_t = ratio of active sediment motion as a fraction of the total time of flow.

Hough (1957) reports unit weights of silty sand and gravel ranging between 89 and 146 lbs/ft^3. Lacking actual in situ measurements, scour depth estimates used the midpoint, 177.5 lbs/ft^3. Widths used the same computations as the hydrology records and are therefore weighted towards the higher flow events. As a simplification, sediment was assumed to move at half the speed of water for all flow rates. Wu (2006) reports on sediment velocities in more detail. Gravel load does not move continuously, but rather in spurts with long pauses of no motion. Annual average computations assumed 1 percent of the width in motion at any time with significant transport occurring 1 percent of the year.

The active layer thickness for use in the DSS system needed to consider effective width as a function of discharge. Calculations first determined if the volume of sediment in transport was adequate to span the volume present in a layer one grain diameter thick over the top width (Equation 3). A diameter of 0.25 foot was assumed for all reaches.

$$V_{s,l} = \frac{Q_s}{\gamma_s \cdot D_s}$$ **Equation 3**

Where,

$V_{s,l}$ = volume contained in a single layer one grain diameter thick;

Q_s = sediment load in mass per time;

γ_s = unit weight of sediment; and

D_s = assumed effective diameter of surface material.

If the volume of sediment in transport was greater than the width required to contain 1 grain thickness, a width ratio (R_w) of 0.5 was assumed. If the volume of sediment transport was less than the top width divided by the grain diameter, the effective width was computed by Equation 4.

$$R_w = \frac{V_s}{V_{s,l}} \cdot R_{w,max}$$ **Equation 4**

Where,

R_w = ratio of width in motion to total top width;

V_s = volume of sediment transport;

$V_{s,l}$ = volume contained in a single layer one grain diameter thick; and

$R_{w,max}$ = maximum width ratio.

The ratio assumptions are rough estimates and grossly simplify actual process, but were chosen to provide reasonable estimates for relative comparisons of the likelihood of scouring redds. Uncertainty in the time and effective width ratios render the final scour depth a poor estimate of actual scour in field conditions. The time in motion was left at 1 percent for all flows, though, in actuality, the time in motion will also vary with flow rate. The discussion section explains limitations in more detail.

Incipient motion applied Shields criteria as reported in Julien (1998). Shear stress from the one-dimensional hydraulics was used to compute a Shields number for each flow rate. Log-log transformed linear regression was used to determine a single flow corresponding to initiation of motion.

Applied energy provides a surrogate for the amount of work done on a channel. Equation 5 shows the computation for applied work for a given flow.

$$\Pi = \sum e_b \cdot R \cdot S_f \cdot v \cdot P \cdot L \cdot t$$ **Equation 5**

Where

Π = Applied work;

e_b = efficiency in transporting sediment;

R = hydraulics radius of the channel;

S_f = friction slope of the channel;

V = main channel velocity;

P = wetted perimeter;

L = longitudinal channel length; and

t = duration of time.

The summation of the stream power for all flow events times the annual duration of the event results in the average annual work performed in transporting sediment. Changes to the amount of work correspond to changes in the sediment yield of a reach.

RESULTS

The best estimate of sediment transport used the Parker (1990) equation with a reference shear stress determined by Mueller, Pitlick, and Nelson (2005). Hiding factors assumed default values from the 1990 regression. Table 5 shows the average annual loads.

The reference shear stress is a site-specific parameter requiring calibration. In the absence of calibration data, prior research including laboratory and field data from Montgomery and Buffington (1997) were used to estimate a range of potential values. Sensitivity tests showed that a 50-percent change in reference shear stress changes the sediment load by an order of magnitude. Variability between equations resulted in less than approximately factor 2 variability for Parker, Wilcock, and Wu. Meyer-Peter and Muller resulted in a one- to two-order of magnitude, increase in transport rate.

The best estimate of transport potential in sand size classes used the Engelund-Hansen methods (see

Table 6).

Table 5. Average annual gravel load best estimate (tons/year) by reach for each scenario

Reach	Black Rock 1	Black Rock 2	Current	No Action	Wymer 1	Wymer 2	Wymer Plus
Yakima R.-18_sr2	15,206	15,206	11,534	12,922	12,976	12,392	12,066
Yakima R.-18_sr1	1,002	1,002	879	960	975	921	919
Yakima R.-17B	6,552	6,552	5,475	6,230	6,069	5,903	5,731
Yakima R.-17A	1,238	1,238	791	889	928	861	910
Yakima R.-17	11,101	11,101	8,472	9,578	9,807	9,238	9,173
Yakima R.-16	13,841	13,841	11,347	12,433	12,827	12,238	11,927
Yakima R.-11C	92	92	53	57	58	55	62
Yakima R.-11B	62	62	43	46	45	45	47
Yakima R.-11A	3,727	3,727	4,316	4,686	3,624	4,971	3,565
Yakima R.-11	432	432	387	415	409	375	432
Yakima R.-10	14,708	14,708	14,918	14,682	12,600	14,625	15,058
Naches R.-5	8,674	8,674	8,492	8,582	8,418	8,492	8,990
Naches R.-4	10,985	10,985	10,489	10,586	10,985	10,497	10,802
Naches R.-3_sr2	20,064	20,064	20,314	20,143	20,878	19,805	21,944
Naches R.-3_sr1	38,910	38,910	37,974	38,489	37,286	38,256	38,160
Naches R.-2	51,292	51,292	50,693	52,225	50,776	49,696	52,780
Yakima R.-6B	4,464	4,464	3,775	3,916	3,602	3,445	3,864
Yakima R.-6A_sr2	53,162	53,162	44,274	46,832	43,482	42,499	50,575
Yakima R.-6A_sr1	136,299	136,299	108,542	114,781	109,494	108,202	129,098
Yakima R.-6	34,248	34,248	28,889	30,695	28,689	28,045	32,688
Yakima R.-5D	2,487	2,487	2,392	2,356	2,204	2,210	2,319
Yakima R.-5B_sr2	167,518	167,518	132,660	141,885	134,399	128,986	154,041
Yakima R.-5B_sr1	2,357	2,357	1,950	2,047	1,926	1,839	2,251
Yakima R.-5	9	8	7	7	6	7	8
Yakima R.-4A	223	207	179	160	152	136	211
Yakima R.-4	2,214	2,094	1,614	1,715	1,646	1,524	2,064
Yakima R.-3_sr2	158	147	111	119	113	104	143
Yakima R.-3_sr1	14,966	14,649	11,137	11,618	11,101	11,107	13,920
Yakima R.-2E	3,734	3,593	2,866	3,003	2,861	2,818	3,555
Yakima R.-2D_sr2	299	283	208	223	213	200	269
Yakima R.-2D_sr1	2,649	2,599	1,931	2,010	1,940	1,978	2,496
Yakima R.-2C_sr2	0	0	0	0	0	0	0
Yakima R.-2C_sr1	245	228	155	164	146	141	216
Yakima R.-2A	7,625	7,059	6,783	6,701	6,969	6,239	6,784
Yakima R.-2	2,978	2,761	3,047	2,854	3,088	2,812	2,583

Reach	Black Rock 1	Black Rock 2	Current	No Action	Wymer 1	Wymer 2	Wymer Plus
Yakima R.-1F	35	32	28	24	24	22	31
Yakima R.-1E	0	0	0	0	0	0	0

Table 6. Transport potential in sand size classes (tons per day)

Reach	Black Rock 1	Black Rock 2	Current	No Action	Wymer 1	Wymer 2	Wymer Plus
Yakima R.-18_sr2	2.22E+7	2.22E+7	2.17E+7	2.25E+7	2.23E+7	2.24E+7	2.08E+7
Yakima R.-18_sr1	1.43E+7	1.43E+7	1.47E+7	1.51E+7	1.49E+7	1.49E+7	1.40E+7
Yakima R.-17B	1.56E+7	1.56E+7	1.56E+7	1.62E+7	1.60E+7	1.60E+7	1.50E+7
Yakima R.-17A	8.32E+6	8.32E+6	8.30E+6	8.56E+6	8.45E+6	8.43E+6	8.02E+6
Yakima R.-17	1.36E+7	1.36E+7	1.26E+7	1.35E+7	1.32E+7	1.32E+7	1.27E+7
Yakima R.-16	1.90E+7	1.90E+7	1.73E+7	1.89E+7	1.86E+7	1.85E+7	1.80E+7
Yakima R.-11C	8.24E+7	8.24E+7	8.42E+7	8.68E+7	8.22E+7	8.61E+7	8.15E+7
Yakima R.-11B	7.63E+7	7.63E+7	7.82E+7	8.07E+7	7.67E+7	8.02E+7	7.58E+7
Yakima R.-11A	1.91E+8	1.91E+8	1.94E+8	1.99E+8	1.93E+8	1.99E+8	1.91E+8
Yakima R.-11	7.13E+7	7.13E+7	7.40E+7	7.61E+7	7.22E+7	7.54E+7	7.13E+7
Yakima R.-10	5.38E+7	5.38E+7	5.68E+7	5.74E+7	5.40E+7	5.71E+7	5.43E+7
Naches R.-5	2.52E+8	2.52E+8	2.53E+8	2.54E+8	2.56E+8	2.54E+8	2.58E+8
Naches R.-4	2.37E+8	2.37E+8	2.38E+8	2.40E+8	2.43E+8	2.39E+8	2.43E+8
Naches R.-3_sr2	2.96E+8	2.96E+8	2.99E+8	3.00E+8	3.03E+8	3.00E+8	3.04E+8
Naches R.-3_sr1	2.41E+8	2.41E+8	2.43E+8	2.44E+8	2.47E+8	2.43E+8	2.47E+8
Naches R.-2	2.10E+8	2.10E+8	2.16E+8	2.18E+8	2.15E+8	2.12E+8	2.15E+8
Naches R.-1	1.72E+8	1.72E+8	1.77E+8	1.79E+8	1.76E+8	1.74E+8	1.77E+8
Yakima R.-8	2.94E+7	2.94E+7	2.37E+7	2.40E+7	2.41E+7	2.35E+7	2.40E+7
Yakima R.-7	5.09E+7	5.09E+7	4.21E+7	4.28E+7	4.19E+7	4.15E+7	4.17E+7
Yakima R.-6B	2.00E+8	2.00E+8	1.82E+8	1.85E+8	1.78E+8	1.78E+8	1.79E+8
Yakima R.-6A_sr2	3.06E+8	3.06E+8	2.65E+8	2.76E+8	2.68E+8	2.68E+8	2.97E+8
Yakima R.-6A_sr1	1.32E+8	1.32E+8	1.17E+8	1.20E+8	1.17E+8	1.18E+8	1.29E+8
Yakima R.-6	4.92E+7	4.92E+7	4.12E+7	4.29E+7	4.17E+7	4.16E+7	4.72E+7
Yakima R.-5D	1.17E+7	1.17E+7	9.51E+6	1.01E+7	9.53E+6	9.45E+6	1.10E+7
Yakima R.-5B_sr2	1.46E+8	1.46E+8	1.23E+8	1.28E+8	1.24E+8	1.23E+8	1.38E+8
Yakima R.-5B_sr1	2.24E+7	2.24E+7	1.82E+7	1.93E+7	1.84E+7	1.79E+7	2.09E+7
Yakima R.-5	6.20E+7	6.00E+7	4.75E+7	4.95E+7	4.76E+7	4.70E+7	5.72E+7
Yakima R.-4A	1.73E+7	1.65E+7	1.29E+7	1.38E+7	1.33E+7	1.29E+7	1.59E+7
Yakima R.-4	3.01E+7	2.95E+7	2.25E+7	2.35E+7	2.25E+7	2.24E+7	2.82E+7
Yakima R.-3_sr2	2.24E+7	2.19E+7	1.75E+7	1.81E+7	1.74E+7	1.74E+7	2.13E+7
Yakima R.-3_sr1	3.45E+6	3.35E+6	2.51E+6	2.64E+6	2.52E+6	2.49E+6	3.18E+6
Yakima R.-2E	1.00E+6	9.63E+5	7.86E+5	8.20E+5	7.86E+5	7.73E+5	9.55E+5
Yakima R.-2D_sr2	7.42E+5	7.05E+5	5.24E+5	5.59E+5	5.35E+5	5.09E+5	6.77E+5
Yakima R.-2D_sr1	4.84E+6	4.72E+6	3.62E+6	3.77E+6	3.65E+6	3.65E+6	4.55E+6
Yakima R.-2C_sr2	1.11E+6	1.06E+6	8.09E+5	8.54E+5	8.23E+5	7.82E+5	1.02E+6
Yakima R.-2C_sr1	3.77E+7	3.64E+7	2.77E+7	2.91E+7	2.82E+7	2.75E+7	3.49E+7
Yakima R.-2A	1.70E+8	1.64E+8	1.35E+8	1.38E+8	1.34E+8	1.28E+8	1.50E+8

Reach	Black Rock 1	Black Rock 2	Current	No Action	Wymer 1	Wymer 2	Wymer Plus
Yakima R.-2	1.28E+8	1.24E+8	1.01E+8	1.04E+8	1.00E+8	9.65E+7	1.13E+8
Yakima R.-1F	7.40E+7	7.24E+7	5.80E+7	5.91E+7	5.67E+7	5.61E+7	6.96E+7
Yakima R.-1E	3.89E+7	3.81E+7	3.13E+7	3.17E+7	3.06E+7	3.07E+7	3.72E+7

On average, Yang's equation predicted 30 percent higher sand transport potential than Engelund-Hansen. Upstream reaches all computed higher transport values with Yang's equation, while in the downstream reaches, results were mixed with computations yielding both higher and lower transport than Engelund-Hansen.

Conversion to EDT parameters required estimating the width of the channel, unit weight of materials, and ratios for the sediment velocity, time in motion, and effective transport width. Table 7 shows the resulting scour depth estimates.

Table 7. Scour depth (feet)

Reach	Top Width (feet)	Flow Velocity (feet/ sec)	Black Rock 1	Black Rock 2	Current	No Action	Wymer 1	Wymer 2	Wymer Plus
Yakima R.-8_sr2	91.5	5.10	0.35	0.35	0.27	0.30	0.30	0.29	0.28
Yakima R.-8_sr1	94.4	4.18	0.03	0.03	0.02	0.03	0.03	0.03	0.03
Yakima R.-17B	78.2	4.71	0.19	0.19	0.16	0.18	0.18	0.17	0.17
Yakima R.-17A	80.2	4.06	0.04	0.04	0.03	0.03	0.03	0.03	0.03
Yakima R.-17	94.6	4.29	0.29	0.29	0.23	0.25	0.26	0.25	0.24
Yakima R.-16	99.0	4.44	0.34	0.34	0.28	0.31	0.31	0.30	0.29
Yakima R.-11C	217.1	4.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Yakima R.-11B	270.8	4.13	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Yakima R.-11A	255.5	5.21	0.03	0.03	0.03	0.04	0.03	0.04	0.03
Yakima R.-11	192.9	4.42	0.01	0.01	0.00	0.01	0.01	0.00	0.01
Yakima R.-10	206.8	4.21	0.18	0.18	0.18	0.18	0.16	0.18	0.19
Naches R.-5	155.6	5.72	0.11	0.11	0.10	0.10	0.10	0.10	0.11

Reach	Top Width (feet)	Flow Velocity (feet/ sec)	Black Rock 1	Black Rock 2	Current	No Action	Wymer 1	Wymer 2	Wymer Plus
Naches R.-4	178.8	5.70	0.12	0.12	0.11	0.11	0.12	0.11	0.11
Naches R.-3_sr2	150.8	6.01	0.24	0.24	0.24	0.24	0.25	0.24	0.26
Naches R.-3_sr1	138.9	6.03	0.50	0.50	0.49	0.50	0.48	0.49	0.49
Naches R.-2	145.2	6.12	0.62	0.62	0.62	0.63	0.62	0.60	0.64
Naches R.-1	141.1	5.90	0.45	0.45	0.44	0.46	0.45	0.44	0.46
Yakima R.-8	174.3	4.57	0.03	0.03	0.02	0.02	0.02	0.02	0.02
Yakima R.-7	168.3	5.02	0.06	0.06	0.05	0.05	0.04	0.04	0.05
Yakima R.-6B	203.2	6.17	0.04	0.04	0.03	0.03	0.03	0.03	0.03
Yakima R.-6A_sr2	183.2	6.62	0.47	0.47	0.39	0.42	0.39	0.38	0.45
Yakima R.-6A_sr1	173.5	5.42	1.56	1.56	1.25	1.32	1.26	1.24	1.48
Yakima R.-6	179.7	5.03	0.41	0.41	0.35	0.37	0.34	0.33	0.39
Yakima R.-5D	305.4	2.93	0.03	0.03	0.03	0.03	0.03	0.03	0.03
Yakima R.-5B_sr2	206.9	5.87	1.49	1.49	1.18	1.26	1.19	1.15	1.37
Yakima R.-5B_sr1	243.9	3.74	0.03	0.03	0.02	0.02	0.02	0.02	0.03
Yakima R.-5	294.9	4.21	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Yakima R.-4A	283.4	3.74	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Yakima R.-4	371.4	3.66	0.02	0.02	0.01	0.01	0.01	0.01	0.02
Yakima R.-3_sr2	447.0	3.37	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Yakima R.-3_sr1	280.9	2.73	0.21	0.21	0.16	0.16	0.16	0.16	0.20
Yakima R.-2E	337.0	2.18	0.05	0.05	0.04	0.04	0.04	0.04	0.05
Yakima R.-2D_sr2	381.2	2.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Yakima R.-2D_sr1	463.8	2.41	0.03	0.03	0.02	0.02	0.02	0.02	0.02

Reach	Top Width (feet)	Flow Velocity (feet/sec)	Black Rock 1	Black Rock 2	Current	No Action	Wymer 1	Wymer 2	Wymer Plus
Yakima R.-2C_sr2	401.2	2.27	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Yakima R.-2C_sr1	462.1	3.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Yakima R.-2A	242.3	6.16	0.06	0.05	0.05	0.05	0.05	0.05	0.05
Yakima R.-2	267.5	5.83	0.02	0.02	0.02	0.02	0.02	0.02	0.02
Yakima R.-1F	310.3	4.50	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Yakima R.-1E	304.1	3.98	0.00	0.00	0.00	0.00	0.00	0.00	0.00

The reported typical range of unit weights for silty sand and gravel material results in plus or minus 50 percent in the unit weight. The subsequent scour depth calculations are subject to the same variability. The ratio between sediment and flow velocity can vary up to near unity for very high transport rates. Though no literature documents time or effective width ratios, a reasonable range of variability might result in a difference of one or two orders of magnitude. Results, therefore, could vary by two orders of magnitude.

Incipient motion used Shields shear stress criteria and a log-log interpolated discharge. In many reaches, the range of flows did not exceed the criteria and discharges were extrapolated, resulting in unreasonably large values. Other cases with small values likely experience some motion at all times. Table 8 shows the results

Table 8. Discharge Causing Incipient Motion Criteria

Reach	D_{84} (mm)	Critical Shields Number	Critical Shear Stress (lb/ft^2)	Armor Disruption (ft^3/s)	Extrapolated
Yakima R.-18_sr2	64.48	0.050	1.09	5,636	
Yakima R.-18_sr1	64.48	0.050	1.09	101,948	yes
Yakima R.-17B	64.48	0.050	1.09	4,778	yes
Yakima R.-17A	64.48	0.050	1.09	9,362	yes
Yakima R.-17	76.39	0.050	1.29	13,392	yes
Yakima R.-16	76.39	0.050	1.29	20,726	yes
Yakima R.-11C	64.00	0.050	1.08	14,416	yes
Yakima R.-11B	43.06	0.047	0.68	7,656	
Yakima R.-11A	43.06	0.047	0.68	8,793	
Yakima R.-11	90.51	0.052	1.59	333,853	yes
Yakima R.-10	92.43	0.052	1.62	35,775	yes

Reach	D_{84} (mm)	Critical Shields Number	Critical Shear Stress (lb/ft^2)	Armor Disruption (ft^3/s)	Extrapolated
Naches R.-5	118.94	0.052	2.09	46,241	yes
Naches R.-4	116.12	0.052	2.04	89,475	yes
Naches R.-3_sr2	40.81	0.047	0.65	701	
Naches R.-3_sr1	40.81	0.047	0.65	977	
Naches R.-2	40.81	0.047	0.65	1,265	
Yakima R.-6B	122.36	0.052	2.15	55,566	yes
Yakima R.-6A_sr2	65.11	0.050	1.10	11,339	
Yakima R.-6A_sr1	41.71	0.047	0.66	8,286	
Yakima R.-6	41.71	0.047	0.66	14,452	
Yakima R.-5D	41.71	0.047	0.66	23,507	
Yakima R.-5B_sr2	41.71	0.047	0.66	6,703	
Yakima R.-5B_sr1	133.58	0.052	2.35	258,003	yes
Yakima R.-5	64.00	0.050	1.08	66,383	yes
Yakima R.-4A	35.94	0.047	0.57	32,233	
Yakima R.-4	0.66	0.048	0.01	2	
Yakima R.-3_sr2	0.66	0.048	0.01	0	
Yakima R.-3_sr1	0.52	0.048	0.01	142	
Yakima R.-2E	0.52	0.048	0.01	0	
Yakima R.-2D_sr2	110.47	0.052	1.94	3,554	yes
Yakima R.-2D_sr1	110.47	0.052	1.94	--	yes
Yakima R.-2C_sr2	57.48	0.050	0.97	191,985	yes
Yakima R.-2C_sr1	99.60	0.052	1.75	--	yes
Yakima R.-2A	61.33	0.050	1.04	13,078	
Yakima R.-2	61.33	0.050	1.04	19,789	
Yakima R.-1F	61.33	0.050	1.04	45,779	yes
Yakima R.-1E	61.33	0.050	1.04	101,951	yes

Applied energy and active layer thickness calculations are provided as a data appendix due to the quantity of data. The surrogate nature of the calculations did not warrant sensitivity studies, as the same assumptions would propagate through all calculations.

Geomorphic work results provided energy expenditure on sediment transport according to flow rate for the USGS DSS. The total work on a system acts as a surrogate for channel activity. In the absence of a full sediment balance, channel activity cannot be evaluated as sustainable (equilibrium), aggradational and degradational. However, for biological purposes on the Yakima, increases in work are expected to be beneficial. The sediment computations provided rating curves to the USGS DSS, but did not compare alternatives. Data tables are too large to reasonably print.

DISCUSSION

Sediment transport analysis used a daily flow record simulating a 20-year period of record. The ability of the record to capture the range of large floods (recurrence intervals greater than 10 to 20 years) is unknown and the analysis does not account for the more extreme events. There is no geomorphic study to identify the significance of extreme events on the Yakima River morphology. Additionally, the impact of a 20-year flood is divided by 20 to represent the average impact per year.

The computation of a sediment load depends up the hydraulics, bed material, transport equation, and transport parameters. Hydraulics used a one-dimensional model with no water surface calibration information in the high-flow range where most sediment transport occurs. In general, calibration to higher flows results in lower roughness estimates and therefore greater velocities and sediment movement. Improved hydraulics would tend to increase sediment loads. Bed material samples measured a 1-meter square. Field conditions typically exhibit high spatial variability. Patches with smaller sizes will move sooner and in larger quantities than larger sizes. Sampling attempted to identify representative patches, but the spatial distribution is unknown. Uncertainty in bed material is assumed to increase uncertainty, but not introduce bias. The selection of a transport equation exerts a smaller influence than the range of variability in the calibration parameters. Although input uncertainty results in absolute computations varying by orders of magnitude, the relative differences between reaches and between scenarios for the same reach are nearly identical. Improvements to load estimates require calibrating the reference shear stress to known transport rates for known hydraulic conditions. Overall, uncertainty in the references shear stress dominates over all other inputs. Computations are assumed to be biased slightly low from hydraulics with an overriding unknown impact from differences between the assumed versus actual reference shear stress. Use of the results is recommended for relative comparisons between scenarios for specific reaches. Comparison between reaches is less robust.

Sediment transport measured reach average values. The models do not capture local effects such as the scour of a riffle with bar formation or subsequent deposition in the adjacent downstream pool. Meander migration and changes in planform are neglected. There can be substantial change within a reach with no net alteration in channel form and process. In other words, although material moves, the width, depth, meander pattern, and pool structure stay the same when looking at the reach as a whole. Higher rates of movement in one area may be cancelled by lower rates in another.

Transport potential represents the ability of the river to move material in the absence of interference from other grain classes and assuming infinite access to sources of material. The capacity indicates the ability of the river to entrain and carry material, still assuming infinite access, but accounting for interactions with other grain classes. The presence of other grain classes will reduce the capacity by one or more orders of magnitude. Hiding of smaller classes by large grains will further reduce capacity. The load measures actual transport considering both interactions between grain classes and limited access to source materials. For the Yakima and Naches Rivers, limited access to source materials will likely reduce sand loads to very small values. None of the transport equations can accurately predict supply-limited conditions. The potential provides a surrogate for the ability to extract sands from gravel-cobble substrates. The EDT and DSS analysis assume the hiding factors and supply limitations remain the same across all scenarios. This assumption is likely to remain true between different reaches.

Estimates of scour depth attempted to quantify the thickness of the layer actively engaged in an exchange of material between the channel bed and water column. The methods used a 1-D mass flux approach on a cross-section basis. In actuality, local mixing may extend the active layer two to three times deeper as 3-D flow patterns causes some grains to move laterally or even upstream. Uncertainty in the assumptions of a time in motion and effective width can change the result by two orders of magnitude and subsume the uncertainty in local exchanges, unit weight, and sediment velocity. Values were selected to provide reasonable estimates of active layer depth. Parameters were held constant across bed material sizes, discharges, and reach geometries. In actuality, the parameters can change substantially. As flow increases, more of the width sees more particles move for a larger fraction of time. Actual movement cannot be estimated at this time. Scour is limited to discrete grain sizes, not a continuum, and may occur in narrow bands rather than across the channel. Fish may avoid these areas when spawning. Calculations are valid for comparison of single reaches between scenarios.

Sediment transport did not examine the balance of material (inflow minus outflow) and the subsequent potential for aggradation or degradation. The analysis evaluated the average annual scour only. In physical systems, upstream supplies may replace scoured material and result in no net change following a high flow event. Alternately the supply and transport may not occur at the same rate resulting in changing channel slope, shape, and planform over time. This analysis used current and immediately forecast conditions and did not account for changes to channel form.

Incipient motion measures the shear stress required to begin rolling or sliding of individual grain classes. Assumptions included critical value, representative grain diameter, and extrapolation to unmodeled values. The Shields diagram provides estimates assuming bed material comprised of uniform materials. The presence of a range of diameters tends to reduce the critical value. Uncertainty in the specific reduction for a given gradation makes using different values unreasonable. The selection of the 84th percentile increases the incipient motion discharge versus using the 50th percentile. Isolated motion may occur at smaller flows, but mass movement requires rolling larger diameters as well. The 1-D hydraulic models did not span a range of shear stresses high enough to indicate motion. Most reaches required extrapolation. Very high discharges can be interpreted as no mass mobilization is possible. Isolated local areas of sediment movement may occur. Reaches with immobile beds are more likely to adjust laterally if bank materials are weak.

Geomorphic work represents a surrogate for the sediment yield of a reach given different hydrologic, hydraulics, and bed material conditions. The parameter provides an integrative means of comparing sediment yield between substantially different conditions. These scenarios consider hydrology only. Areas performing excessive work may result in bed degradation, bank erosion, or bed coarsening. Areas with insufficient work may result in deposition, avulsion, or narrowing. Determining an ideal amount of work requires evaluating sediment movement throughout a basin. In the absence of such modeling, field indicators can suggest whether a reach might require more or less work. However, such limited analysis cannot determine when a reach might cross a threshold and overcorrect too far.

CONCLUSION

In general, the Yakima River exhibited low annual rates of sediment transport in most reaches. Geomorphic activity occurs primarily through rare large floods. Long recovery periods are likely required after large disturbances. Results show small changes between alternate flow scenarios.

Sediment transport rates provided a measure of gravel motion in the channel. No information was available to calibrate the loads. Transport potential provides an estimate of the ability to remove fine materials from the surface. To estimate the likelihood of scouring redds, the computation of an active layer thickness provided a relative depth. However, uncertainty in the input parameters renders the calculation a relative surrogate rather than a concrete physical value. Incipient motion criteria estimates the flow rate required to mobilize bed material. Most reaches required extrapolation from modeled values and were unlikely to be seen in the storage study scenarios. Geomorphic work provides a means of comparing between multiple flow regimes; for example, a large amount of mobilization occurring rarely, versus a more moderate amount occurring more often. Target values of work were not estimated, but, from field indicators, a user can estimate whether a reach requires more or less transport and select scenarios that meet the objectives.

Without extensive field calibration, sediment transport computations are relative and primarily accurate for comparisons between scenarios. Results should not be assumed to represent absolute physical conditions. For example, a correct interpretation of results may show a 50-percent change, but it should not be assumed that one would measure 2 versus 4 feet of scour. This level of analysis is adequate for comparing alternatives.

Further study of the geomorphic and sediment transport processes may measure field conditions to calibrate a transport relationship. Quantification of sediment sources can provide information on potential areas supplying sand materials clogging gravel substrates. A geomorphic sediment budget or mobile-boundary model can better estimate geomorphic changes from large events or suggest methods to address inadequacies in physical habitat. Riffle-pool scale 2-D sediment transport for a few select sites may provide information on local habitat processes to avoid or replicate.

DATA APPENDIX

The following electronic data sets accompany the report (attached DVD) and are organized as follows:

- Data
    - Aerials
        - 2004 Color Infrared Photography
    - Reference
        - Cross-Section Layout
        - EDT Reach Designations
        - River Mile
    - Bed Material
    - Hydraulics
        - HEC-RAS Models
    - Hydrology
        - RiverWare Output
    - Transport
- Documentation
    - Yakima River Sediment Transport

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APPENDIX A – EDT REACH LAYOUTS

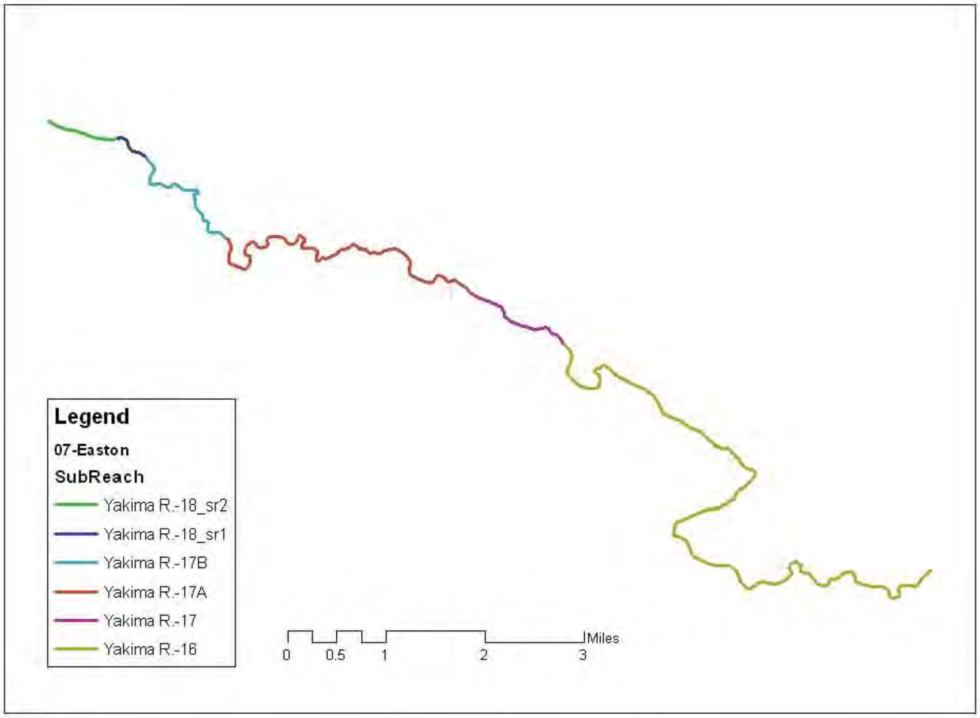


Figure 3. Easton

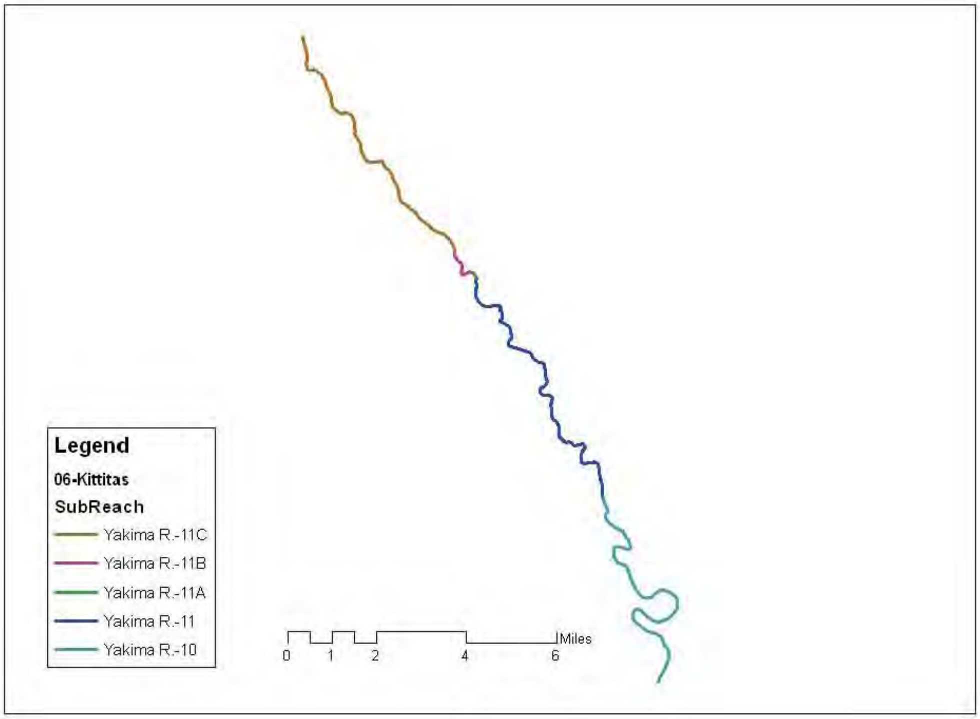


Figure 4. Kittitas

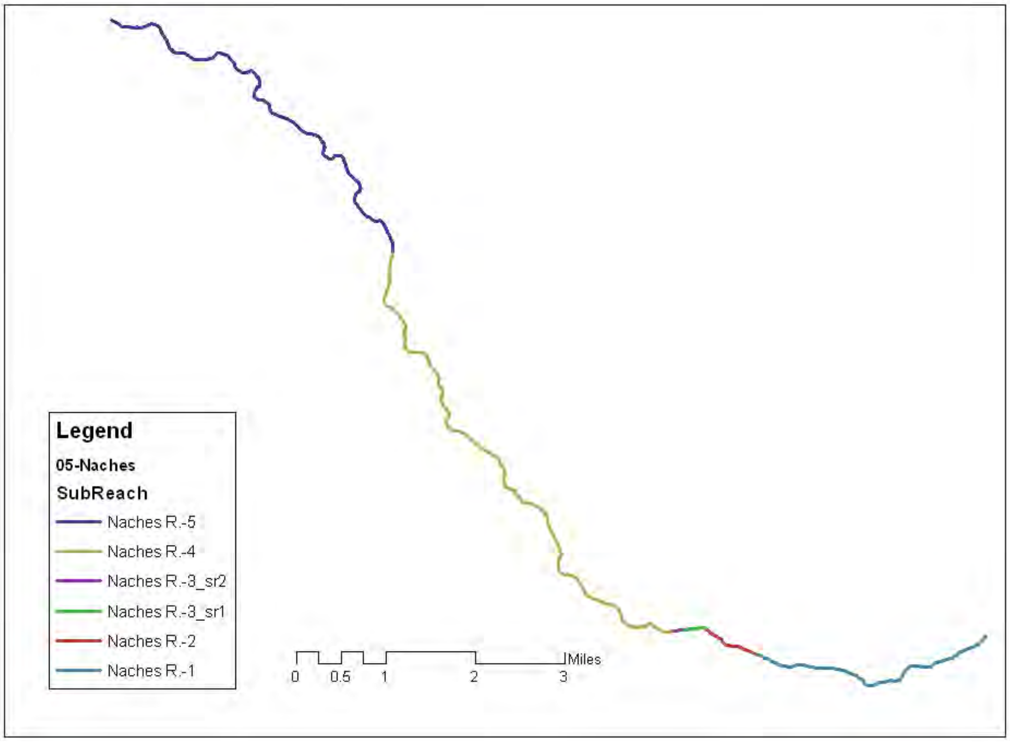


Figure 5. Naches

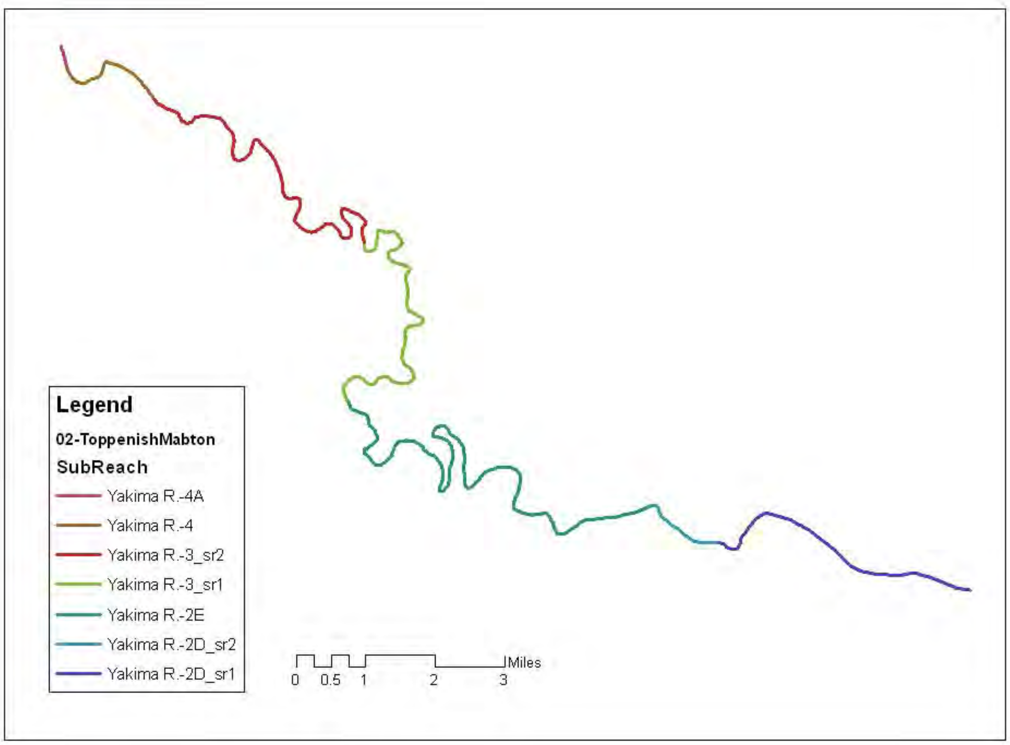


Figure 6. Topenish to Mabton

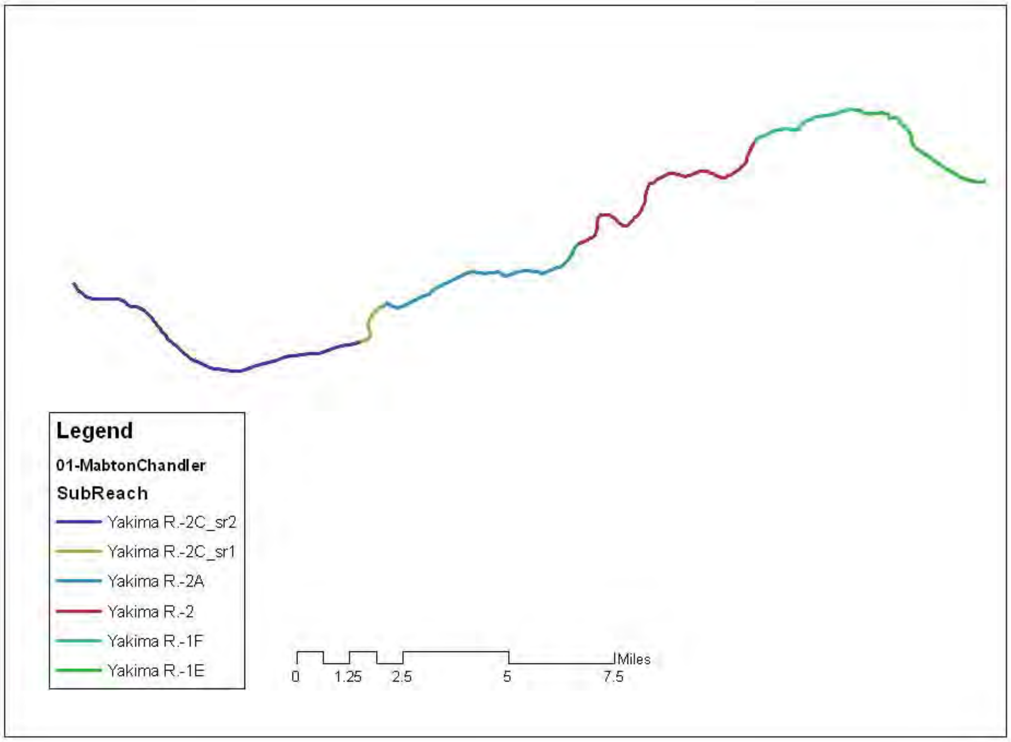


Figure 7. Mabton to Chandler

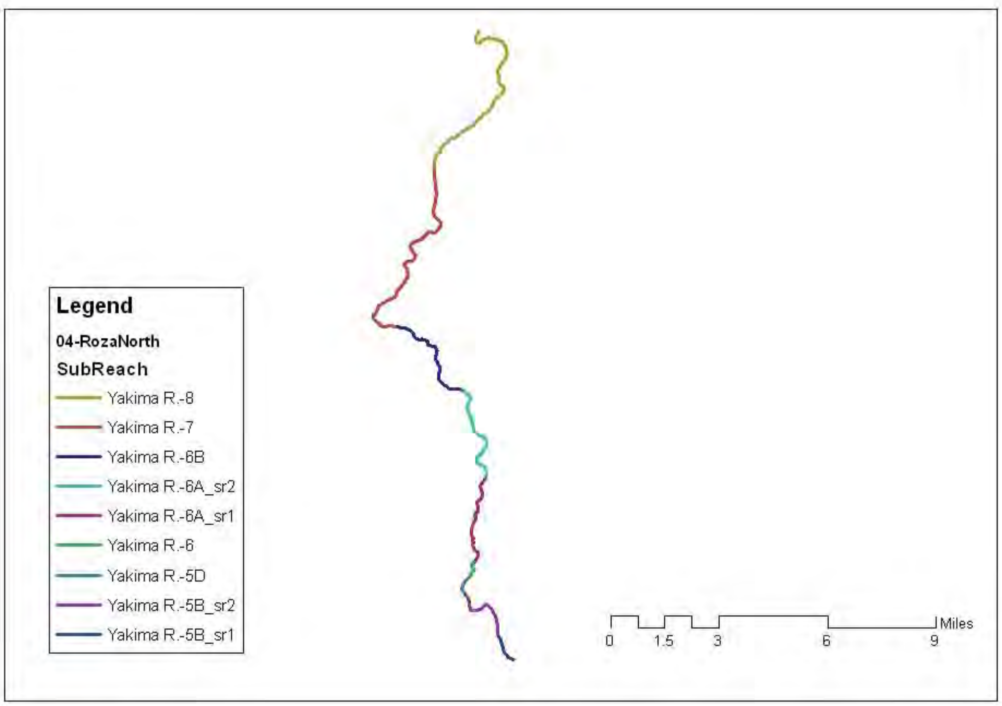


Figure 8. Rosa North

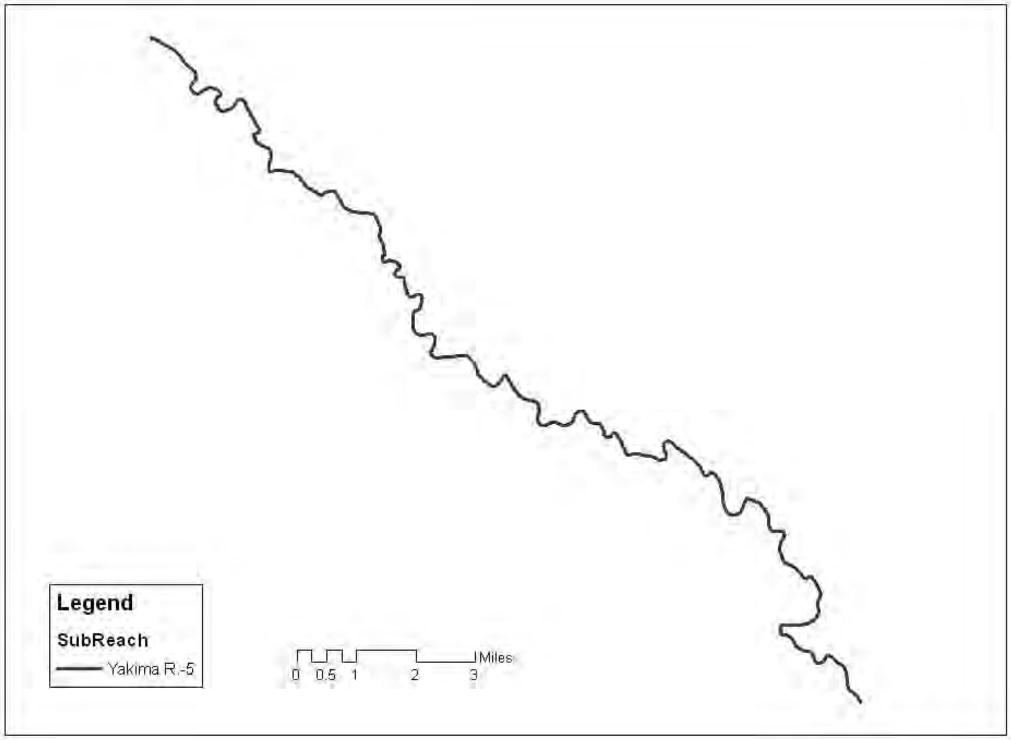


Figure 9. Rosa South

APPENDIX B – SEDIMENT SAMPLING

Volumetric samples of bed material were collected from within a specific photographed area such that comparisons could be made between the photo-sieving method and volumetric sampling. The surface bed material samples were collected in the Yakima basin from the Naches and Yakima Rivers. The process for collecting the sample began with a photograph of a one square yard area, bordered with a ruler graduated in inches (Figure 10). The surface material was then removed from within the square (Figure 11) and set aside. A field sieve (Figure 12) with square openings of 64 and 32 mm was used to separate material finer than 64 mm. Bed material larger than 64 mm was hand sieved using a gravelometer (Figure 13) or measuring the B-axis if material was larger than 128 mm. All material from each individual size class was then weighed with a scale suspended from a tripod (Figure 14) and data were recorded and the tarp was used to segregate the size classes during sorting. Surface material smaller than 32 mm was taken to a lab for grain size analysis.

After the grain size analysis was performed in the lab for the smaller size fractions, the data were combined with the field-collected data for the larger size fractions. These data provided a complete grain size distribution of the surface material sampled from within the photographed area. Some points along the distribution were obtained using a logarithmic interpolation. The distributions from the volumetric sample were then compared to the results from the photo-sieving method.

Figure 10. Photograph of the sampling area prior to the removal of the surface material

Figure 11. Photograph of the sampling area after removal of the surface material

Figure 12. Field sieve used for fractions finer than 64 mm. The 32-mm screen is shown

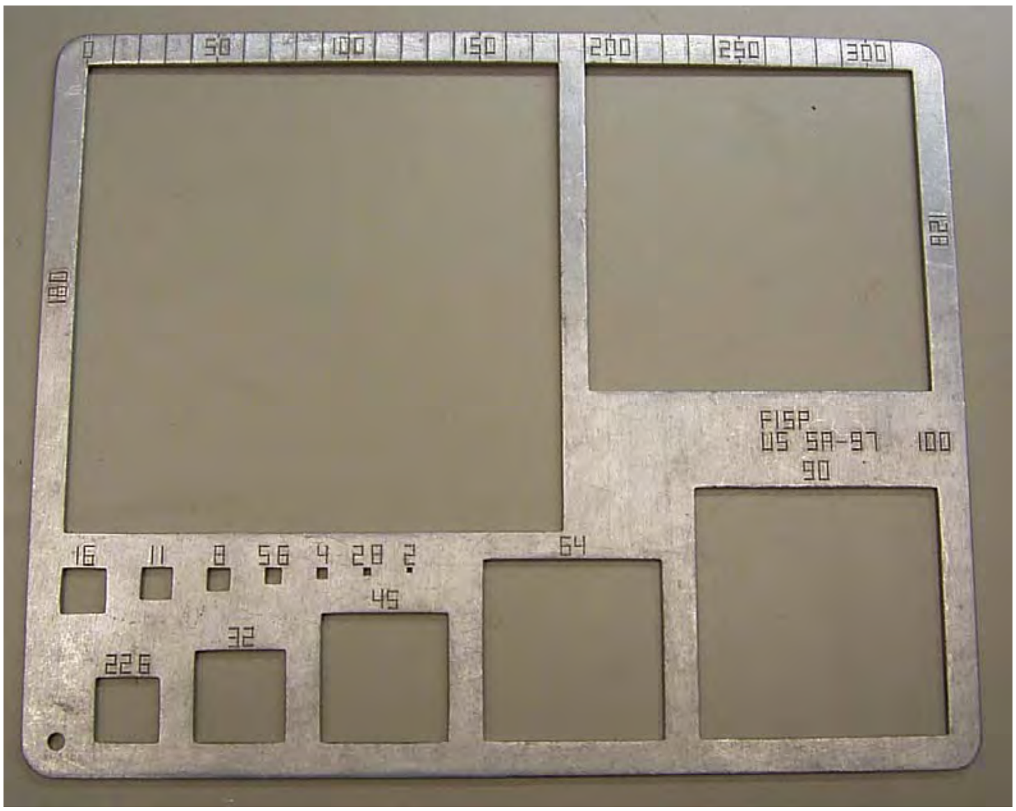
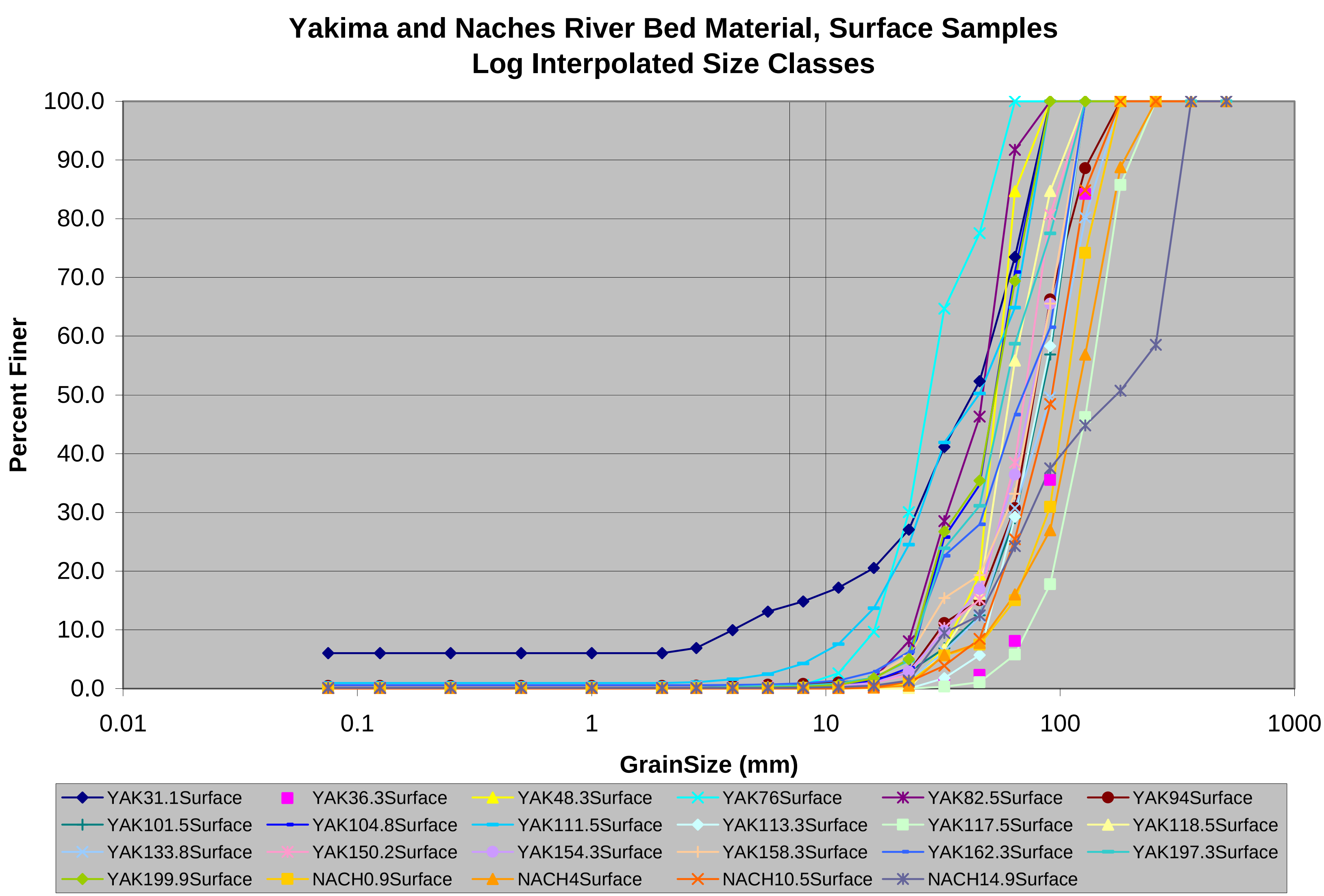


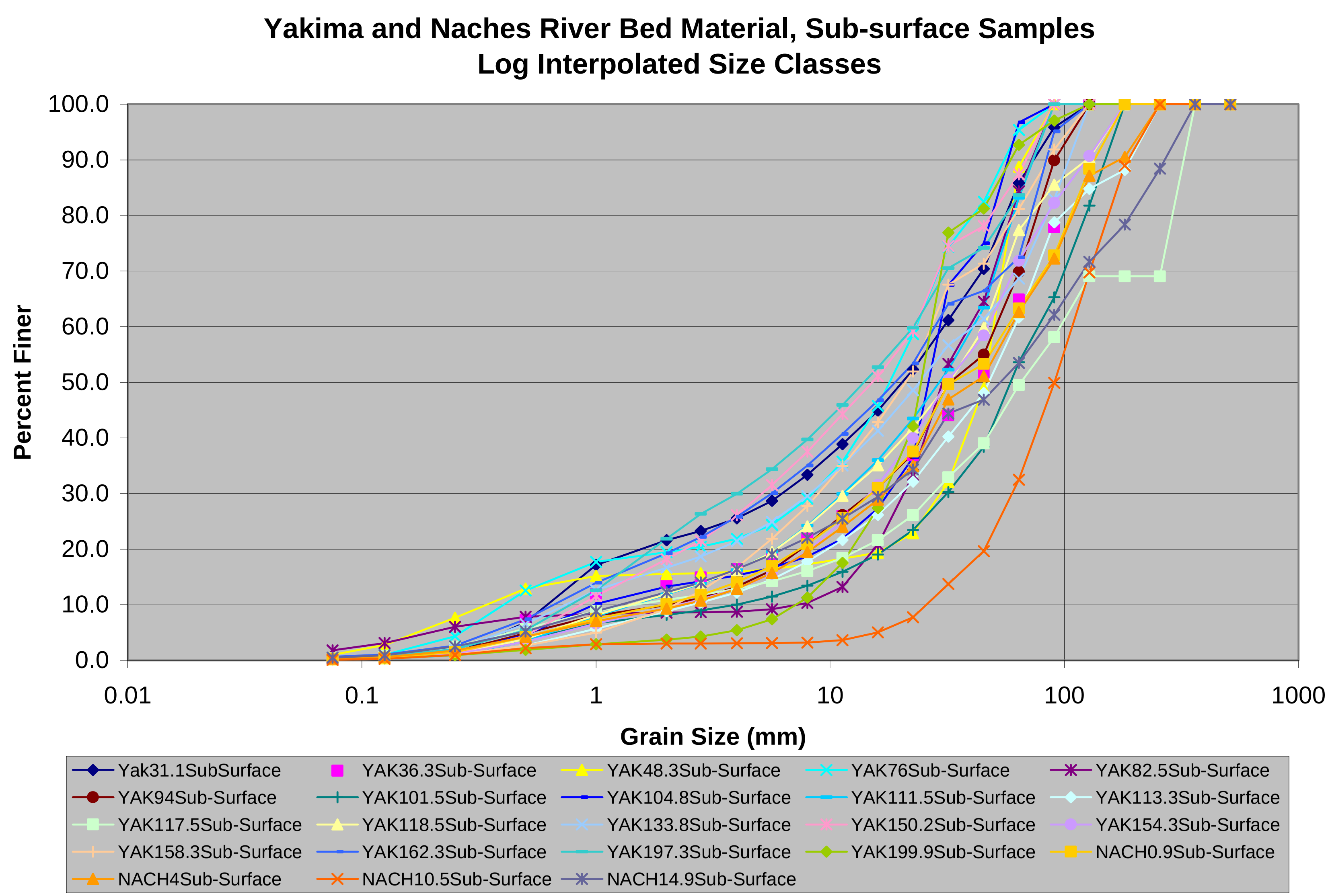
Figure 13. Gravelometer used to sieve the larger size fractions

Figure 14. Photograph of the field sampling setup.

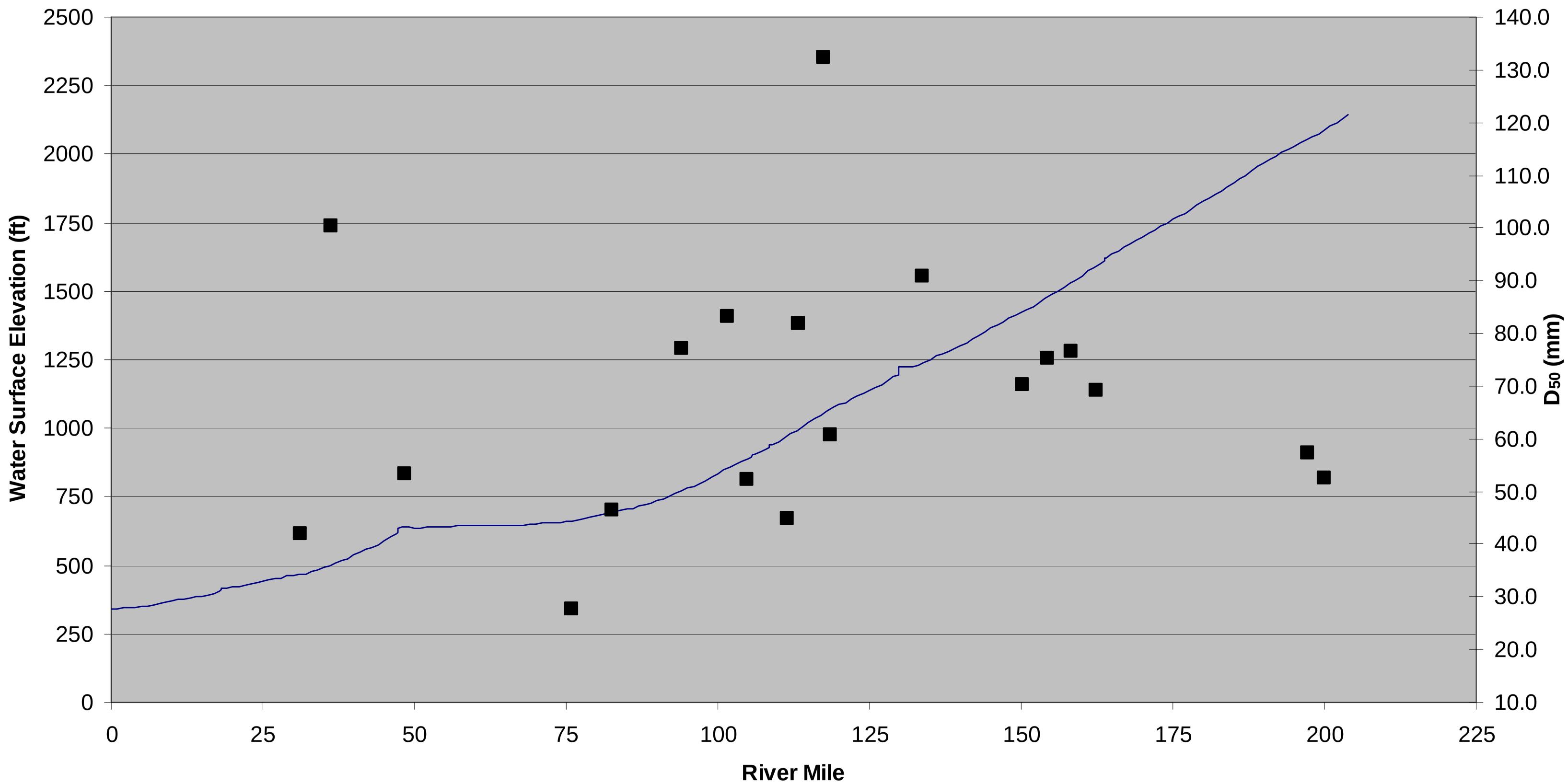
Key	River	Station	Layer	LOG INTERP PERCENT PASSING																						d84(mm)	d50(mm)	d16(mm)	d50class
				512	362.0	256	181.0	128	90.5	64	45.3	32	22.6	16	11.3	8	5.65	4	2.8	2	1	0.5	0.25	0.125	0.075				
YAK31.1Surface	YAK	31.1	Surface	100.0	100.0	100.0	100.0	100.0	100.0	73.5	52.4	41.1	27.1	20.5	17.2	14.8	13.1	9.9	6.9	6.0	6.0	6.0	6.0	6.0	6.0	73.4	42.1	9.5	vcg
YAK31.1Sub-Surface	YAK	31.1	Sub-Surface	100.0	100.0	100.0	100.0	100.0	95.8	85.8	70.4	61.2	52.3	44.9	38.9	33.4	28.7	25.5	23.3	21.6	17.1	6.8	1.1	0.2	0.1	61.4	20.3	0.9	cg
YAK36.3Surface	YAK	36.3	Surface	100.0	100.0	100.0	100.0	84.2	35.5	8.1	2.3	1.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	127.8	100.3	70.7	sm cob
YAK36.3Sub-Surface	YAK	36.3	Sub-Surface	100.0	100.0	100.0	100.0	100.0	77.9	64.9	51.7	44.0	36.9	30.9	26.0	21.9	18.6	16.4	14.9	13.9	12.0	7.3	2.3	0.6	0.3	99.6	41.9	3.6	vcg
YAK48.3Surface	YAK	48.3	Surface	100.0	100.0	100.0	100.0	100.0	100.0	84.7	19.4	6.8	0.9	0.3	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	63.8	53.2	41.2	vcg
YAK48.3Sub-Surface	YAK	48.3	Sub-Surface	100.0	100.0	100.0	100.0	100.0	100.0	88.7	48.9	32.0	22.8	19.3	18.3	17.3	16.4	15.9	15.7	15.5	15.2	12.9	7.6	2.8	1.0	61.4	45.7	4.3	vcg
YAK56.9Surface	YAK	56.9	Surface	100.0	100.0	100.0	89.3	54.1	34.4	17.1	6.9	3.6	2.2	1.5	1.0	0.6	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	171.8	119.1	61.7	sm cob
YAK56.9Sub-Surface	YAK	56.9	Sub-Surface	100.0	100.0	100.0	100.0	87.7	79.0	71.9	63.6	58.4	50.4	43.1	36.9	31.8	27.6	24.8	22.8	21.6	19.6	8.4	1.1	0.2	0.0	110.5	22.2	0.8	cg
YAK59.1	YAK	59.1	one sample	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	99.9	99.9	99.7	98.7	65.5	13.5	1.1	0.2	0.7	0.4	0.3	ms
YAK63.5	YAK	63.5	one sample	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0	99.7	99.1	97.2	89.7	62.3	26.8	11.1	5.9	0.9	0.4	0.2	ms
YAK76Surface	YAK	76	Surface	100.0	100.0	100.0	100.0	100.0	100.0	100.0	77.5	64.7	30.0	9.7	2.6	0.6	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	50.0	27.6	17.8	cg
YAK76Sub-Surface	YAK	76	Sub-Surface	100.0	100.0	100.0	100.0	100.0	100.0	95.4	82.5	74.4	58.6	45.7	35.7	29.1	24.4	21.8	20.4	19.4	17.7	12.5	4.3	1.0	0.5	47.2	17.9	0.8	cg
YAK82.5Surface	YAK	82.5	Surface	100.0	100.0	100.0	100.0	100.0	100.0	91.7	46.3	28.5	8.0	1.7	0.3	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	60.3	46.5	25.9	vcg
YAK82.5Sub-Surface	YAK	82.5	Sub-Surface	100.0	100.0	100.0	100.0	100.0	100.0	84.4	64.5	53.3	33.3	20.8	13.2	10.3	9.2	8.7	8.6	8.6	8.4	7.8	6.0	3.1	1.8	63.6	30.2	12.8	cg
YAK94Surface	YAK	94	Surface	100.0	100.0	100.0	100.0	88.6	66.3	30.7	15.0	11.1	2.9	1.6	1.0	0.8	0.7	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5	119.2	77.2	46.2	sm cob
YAK94Sub-Surface	YAK	94	Sub-Surface	100.0	100.0	100.0	100.0	100.0	89.9	69.8	55.0	49.8	37.2	31.1	26.1	20.8	16.2	13.3	11.2	9.9	8.1	4.9	1.6	0.5	0.3	81.7	32.5	5.5	vcg
YAK101.5Surface	YAK	101.5	Surface	100.0	100.0	100.0	100.0	100.0	56.9	29.0	12.5	6.8	2.9	1.0	0.4	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	112.5	83.1	48.7	sm cob
YAK101.5Sub-Surface	YAK	101.5	Sub-Surface	100.0	100.0	100.0	100.0	81.8	65.3	53.6	38.4	30.3	23.5	19.0	15.9	13.4	11.5	10.0	9.0	8.2	6.7	3.6	1.1	0.3	0.2	133.6	59.0	11.4	vcg
YAK104.8Surface	YAK	104.8	Surface	100.0	100.0	100.0	100.0	100.0	100.0	70.9	34.7	25.8	3.5	1.3	0.6	0.3	0.2	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	74.8	52.4	27.5	vcg
YAK104.8Sub-Surface	YAK	104.8	Sub-Surface	100.0	100.0	100.0	100.0	100.0	100.0	96.7	75.0	67.5	36.5	27.3	21.9	18.7	16.7	15.3	14.2	13.3	10.1	4.5	1.5	0.8	0.6	52.2	26.3	4.8	cg
YAK111.5Surface	YAK	111.5	Surface	100.0	100.0	100.0	100.0	100.0	100.0	64.9	50.2	41.9	24.5	13.7	7.6	4.2	2.4	1.6	1.1	0.9	0.9	0.9	0.9	0.9	0.9	77.3	44.8	17.2	vcg
YAK111.5Sub-Surface	YAK	111.5	Sub-Surface	100.0	100.0	100.0	100.0	100.0	100.0	83.2	63.4	52.3	43.5	36.0	29.9	24.2	19.5	16.2	13.8	11.8	7.9	3.4	0.9	0.2	0.1	65.1	29.3	3.9	cg
YAK113.3Surface	YAK	113.3	Surface	100.0	100.0	100.0	100.0	100.0	58.3	29.3	5.7	1.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	112.1	82.0	52.7	sm cob
YAK113.3Sub-Surface	YAK	113.3	Sub-Surface	100.0	100.0	100.0	88.2	84.8	78.8	61.7	48.0	40.2	32.1	26.1	21.6	17.8	14.6	12.2	10.4	8.8	5.7	2.7	1.0	0.3	0.2	122.4	47.6	6.6	vcg
YAK117.5Surface	YAK	117.5	Surface	100.0	100.0	100.0	85.8	46.2	17.8	5.8	1.1	0.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	178.2	132.3	86.0	lg cob
YAK117.5Sub-Surface	YAK	117.5	Sub-Surface	100.0	100.0	69.1	69.1	69.1	58.1	49.5	39.0	32.9	26.1	21.6	18.4	16.0	14.2	12.9	11.8	10.9	8.9	5.7	2.5	0.8	0.4	302.7	65.4	8	sm cob
YAK118.5Surface	YAK	118.5	Surface	100.0	100.0	100.0	100.0	100.0	84.7	55.8	16.2	6.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	89.7	60.8	45.0	vcg
YAK118.5Sub-Surface	YAK	118.5	Sub-Surface	100.0	100.0	100.0	100.0	90.3	85.5	77.4	59.7	49.7	41.8	35.1	29.5	24.1	19.5	16.2	13.8	11.9	8.1	3.8	1.1	0.3	0.1	84.9	32.3	3.9	vcg
YAK133.8Surface	YAK	133.8	Surface	100.0	100.0	100.0	100.0	80.2	49.6	30.7	12.2	6.3	1.3	0.4	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	136.8	91.0	48.6	sm cob
YAK133.8Sub-Surface	YAK	133.8	Sub-Surface	100.0	100.0	100.0	100.0	100.0	83.0	68.7	61.4	56.7	48.6	41.3	35.0	29.5	24.9	21.4	18.7	16.6	12.7	6.5	1.9	0.5	0.3	92.4	24.0	1.8	cg
YAK150.2Surface	YAK	150.2	Surface	100.0	100.0	100.0	100.0	100.0	80.7	38.5	15.2	10.3	2.3	1.0	0.4	0.3	0.3	0.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2	96.1	70.3	45.8	sm cob
YAK150.2Sub-Surface	YAK	150.2	Sub-Surface	100.0	100.0	100.0	100.0	100.0	100.0	87.4	78.1	74.5	59.2	51.1	44.3	37.5	31.5	26.1	21.5	18.2	11.5	4.4	1.3	0.4	0.2	56.4	15.1	1.6	mg
YAK154.3Surface	YAK	154.3	Surface	100.0	100.0	100.0	100.0	100.0	65.5	36.4	16.9	9.8	2.9	1.0	0.4	0.2	0.1	0.1	0.1	0.0	0.0	0.0	0.0	0.0	0.0	109.0	75.2	43.2	sm cob
YAK154.3Sub-Surface	YAK	154.3	Sub-Surface	100.0	100.0	100.0	100.0	90.7	82.3	71.8	58.4	50.4	40.0	31.5	25.0	19.7	15.5	12.9	11.0	9.4	6.6	3.4	1.1	0.4	0.3	97.2	31.6	5.9	cg
YAK158.3Surface	YAK	158.3	Surface	100.0	100.0	100.0	100.0	100.0	65.6	33.2	19.3	15.4	5.6	2.1	0.7	0.3	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	109.0	76.6	33.7	sm cob
YAK158.3Sub-Surface	YAK	158.3	Sub-Surface	100.0	100.0	100.0	100.0	100.0	91.8	81.2	71.3	67.6	51.9	42.8	34.9	27.8	21.9	16.7	12.5	9.2	5.0	2.7	1.0	0.3	0.1	70.2	21.0	3.8	cg
YAK162.3Surface	YAK	162.3	Surface	100.0	100.0	100.0	100.0	100.0	61.5	46.6	28.0	22.6	6.2	2.9	1.4	0.9	0.7	0.6	0.6	0.6	0.6	0.6	0.6	0.6	0.6	110.8	69.2	27.8	sm cob
YAK162.3Sub-Surface	YAK	162.3	Sub-Surface	100.0	100.0	100.0	100.0	100.0	95.1	72.4	66.4	64.1	53.4	46.7	40.7	35.0	30.1	25.8	22.2	19.2	13.9	7.4	2.6	1.1	0.7	76.4	19.0	1.3	cg
YAK197.3Surface	YAK	197.3	Surface	100.0	100.0	100.0	100.0	100.0	77.5	58.7	31.1	23.9	4.7	1.9	0.9	0.6	0.5	0.3	0.2	0.1	0.1	0.1	0.1	0.1	0.1	100.0	57.4	27.7	vcg
YAK197.3Sub-Surface	YAK	197.3	Sub-Surface	100.0	100.0	100.0	100.0	100.0	100.0	83.6	74.1	70.5	59.8	52.7	45.9	39.7	34.4	30.0	26.3	21.8	12.6	5.4	2.0	0.8	0.4	64.5	13.9	1.3	mg
YAK199.9Surface	YAK	199.9	Surface	100.0	100.0	100.0	100.0	100.0	100.0	69.4	35.4	26.7	5.0	1.7	0.6	0.3	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	75.5	52.5	27.0	vcg
YAK199.9Sub-Surface	YAK	199.9	Sub-Surface	100.0	100.0	100.0	100.0	100.0	97.1	92.7	81.2	76.9	42.1	27.4	17.5	11.3	7.4	5.4	4.3	3.7	2.9	1.9	0.9	0.4	0.3	49.2	24.5	10.4	cg
NACH0.9Surface	NACH	0.9	Surface	100.0	100.0	100.0	100.0	74.2	30.9	15.0	7.5	5.6	1.0	0.4	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	146.0	105.4	65.4	sm cob
NACH0.9Sub-Surface	NACH	0.9	Sub-Surface	100.0	100.0	100.0	100.0	88.4	72.8	63.3	53.3	49.6	37.5	31.0	25.6	20.8	17.0	14.0	11.7	10.2	7.5	4.2	1.5	0.5	0.3	116.1	33.1	5.0	vcg
NACH4Surface	NACH	4	Surface	100.0	100.0	100.0	88.8	56.9	27.0	16.0	7.8	5.7	0.5	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	171.9	118.2	64	sm cob
NACH4Sub-Surface	NACH	4	Sub-Surface	100.0	100.0	100.0	90.5	87.2	72.2	62.6	51.1	46.9	34.9	28.9	24.0	19.5	15.7	12.9	10.7	9.3	7.0	4.3	1.7	0.6	0.3	118.9	41.4	5.8	vcg
NACH10.5Surface	NACH	10.5	Surface	100.0	100.0	100.0	100.0	84.8	48.4	25.4	8.5	3.9	1.1	0.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	127.0	91.9	52.8	sm cob
NACH10.5Sub-Surface	NACH	10.5	Sub-Surface	100.0	100.0	100.0	88.9	69.7	49.9	32.5	19.6	13.7	7.7	5.0	3.6	3.2	3.1	3.1	3.0	3.0	2.9	2.2	0.9	0.3	0.1	165.6	90.7	36.5	sm cob
NACH14.9Surface	NACH	14.9	Surface	100.0	100.0	58.5	50.7	44.8	37.5	24.3	12.5	9.5	1.3	0.5	0.2	0.2	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	316.7	173.4	50.2	lg cob
NACH14.9Sub-Surface	NACH	14.9	Sub-Surface	100.0	100.0	88.4	78.3	71.7	62.1	53.5	46.9	44.4	34.3	29.4	25.5	22.0	19.1	16.4	14.0	12.2	8.9	5.2	2.5	0.9	0.5	220.0	53.3	3.8	vcg



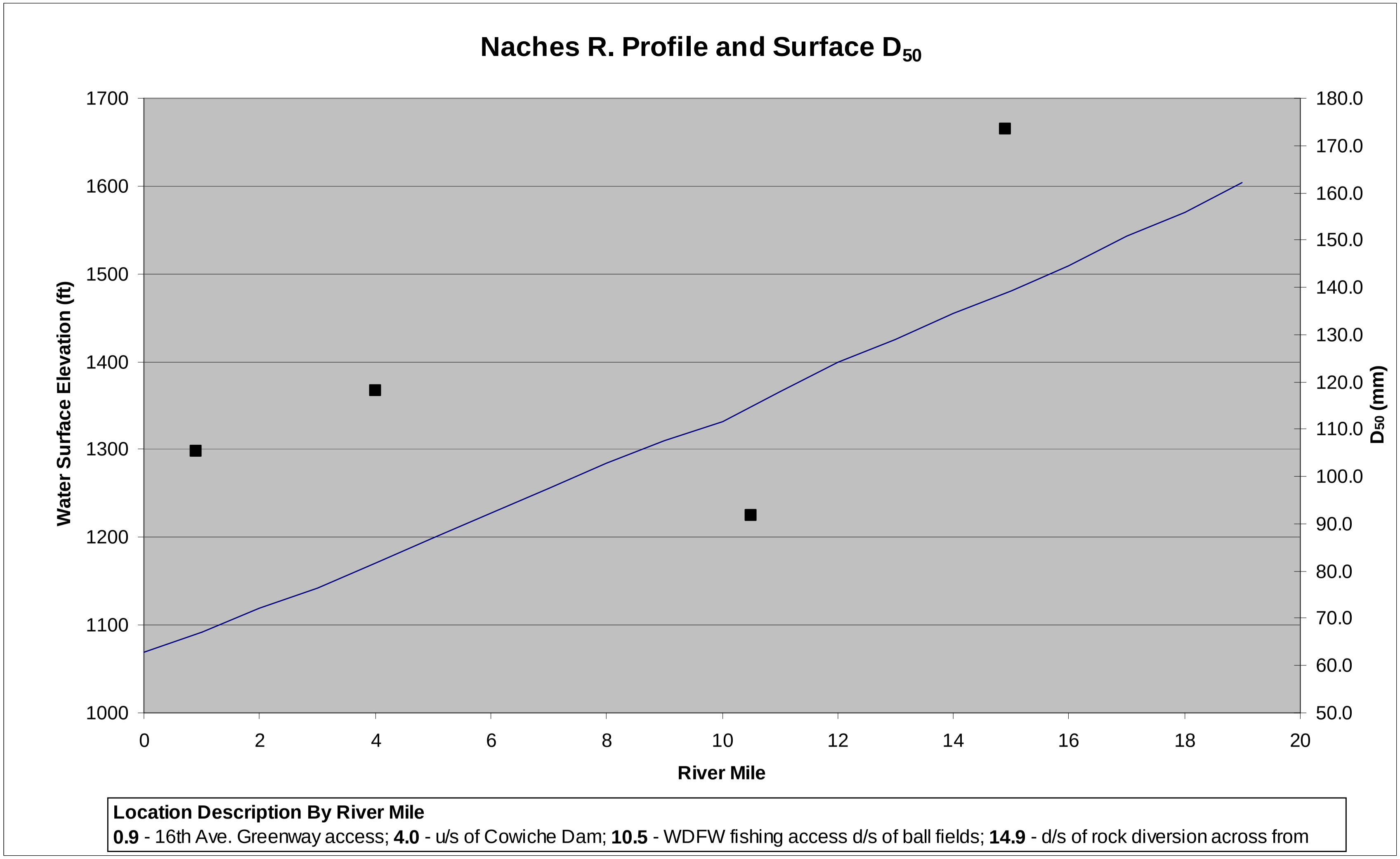
Yakima and Naches River Bed Material, Surface Samples
Log Interpolated Size Classes
Percent Finer
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
0.01
0.1
1
10
100
1000
GrainSize (mm)
YAK31.1Surface
YAK36.3Surface
YAK48.3Surface
YAK76Surface
YAK82.5Surface
YAK94Surface
YAK101.5Surface
YAK104.8Surface
YAK111.5Surface
YAK113.3Surface
YAK117.5Surface
YAK118.5Surface
YAK133.8Surface
YAK150.2Surface
YAK154.3Surface
YAK158.3Surface
YAK162.3Surface
YAK197.3Surface
YAK199.9Surface
NACH0.9Surface
NACH4Surface
NACH10.5Surface
NACH14.9Surface


Yakima and Naches River Bed Material, Sub-surface Samples
Log Interpolated Size Classes
Percent Finer
100.0
90.0
80.0
70.0
60.0
50.0
40.0
30.0
20.0
10.0
0.0
0.01
0.1
1
10
100
1000
Grain Size (mm)
Yak31.1SubSurface
YAK36.3Sub-Surface
YAK48.3Sub-Surface
YAK76Sub-Surface
YAK82.5Sub-Surface
YAK94Sub-Surface
YAK101.5Sub-Surface
YAK104.8Sub-Surface
YAK111.5Sub-Surface
YAK113.3Sub-Surface
YAK117.5Sub-Surface
YAK118.5Sub-Surface
YAK133.8Sub-Surface
YAK150.2Sub-Surface
YAK154.3Sub-Surface
YAK158.3Sub-Surface
YAK162.3Sub-Surface
YAK197.3Sub-Surface
YAK199.9Sub-Surface
NACH0.9Sub-Surface
NACH4Sub-Surface
NACH10.5Sub-Surface
NACH14.9Sub-Surface

Yakima River Profile and Surface D_{50}



Location Description By River Mile
31.1 - u/s Benton City Br.; **36.3** - Chandler P.P.; **48.3** - u/s Prosser Dam; **76.0** - WDFW Property; **94.0** - d/s Toppenish Br.; **101.5** - u/s Wapato Br.; **104.8** - Boat launch d/s Sunnyside Dam; **111.5** - nr. Edler Ponds; **113.3** - u/s S.R. 24 Br.; **117.5** - d/s Naches mouth; **118.5** - d/s Selah; **133.8** - Big Pine Rec. Area; **150.2** - u/s Ringer boat launch; **154.3** - d/s Schaake property; **158.3** - KOA; **162.3** - u/s I-90 crossing; **197.3** - d/s Ensign Ranch; 199.9 - Shady/Pine Glen


Naches R. Profile and Surface D_{50}
Water Surface Elevation (ft)
1700
1600
1500
1400
1300
1200
1100
1000
D_{50} (mm)
180.0
170.0
160.0
150.0
140.0
130.0
120.0
110.0
100.0
90.0
80.0
70.0
60.0
50.0
0
2
4
6
8
10
12
14
16
18
20
River Mile
Location Description By River Mile
0.9 - 16th Ave. Greenway access; **4.0** - u/s of Cowiche Dam; **10.5** - WDFW fishing access d/s of ball fields; **14.9** - d/s of rock diversion across from

APPENDIX C – HYDROLOGY PROCESSING

Hydrology used mean daily values provided from Riverware simulations as the basis for creating average annual flow duration curves for the drainages of each tributary. Ungaged sites used flow duration curves from nearby basins scaled according to the square root of the ratio of drainage areas.

Mean Daily to Instantaneous Transformation

Using mean daily flow values to compute a sediment transport rate would under-predict total loads due to the nonlinear relationship between sediment transport and discharge. A transformation to an instantaneous time series while preserving volume provides an improved estimate. Figure 15 shows the parameters involved.

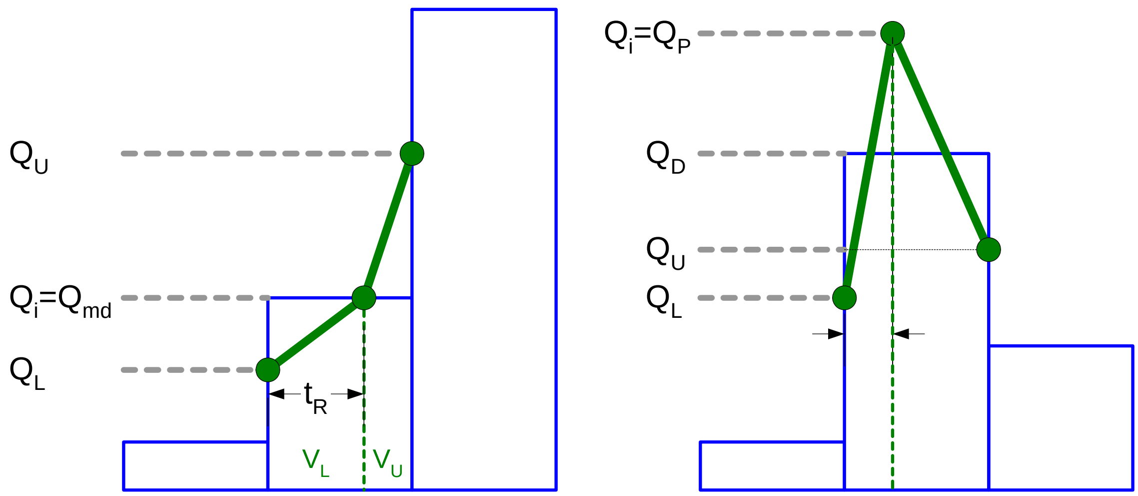


Figure 15. Instantaneous discharge versus mean daily value for rising or falling limbs

The instantaneous discharge at the upper, U, and lower, L, bounds of the mean daily flow record are computed by averaging with the adjacent mean daily flow records. The total daily volume equals the mean daily flow rate, Q_{md}, times the duration of 1 day. Splitting the day into two periods results in a volume of water passing during the first period, V_L, and a volume passing during the second period, V_U. Conservation of volume, Equation 0-6, provides a relationship between the time ratio (t_R), intermediate instantaneous discharge (Q_i), and the instantaneous discharges at the upper and lower boundary of the mean daily flow period (Q_L and Q_U), Equation 0-7.

$$V_D = V_L + V_U$$ **Equation 0-6**

$$Q_{md} \cdot (t_U - t_L) = \frac{1}{2}(Q_L + Q_i)\cdot(t_U - t_L)\cdot(t_R) + \frac{1}{2}(Q_U + Q_i)\cdot(t_U - t_L)\cdot(1 - t_R)$$

$$t_R = \frac{2 \cdot Q_{md} - Q_U - Q_i}{Q_L - Q_U}$$ **Equation 0-7**

Where,

V_D = volume of water computed from the mean daily flow;

V_L = volume of water in the first time period;

V_U = volume of water in the second period;

Q_{md} = mean daily discharge;

t_U = time at the upper boundary;

t_L = time at the lower boundary;

Q_L = instantaneous discharge computed at the start of the day;

Q_i = intermediate instantaneous discharge;

Q_U = instantaneous discharge computed at the end of the day;

Q_P = peak discharge;

t_R = time ratio between the time of day for flows less than the instantaneous discharge versus the total time.

For rising and falling limbs, the instantaneous discharge, Q_i, equals the mean daily flow. For a peak or a trough, the intermediate discharge must be estimated. If no suitable method is available for estimating the intermediate flow, Equation 0-8 solves the conservation of volume equations for discharge given a time ratio.

$$Q_i = 2 \cdot Q_{md} + t_R \cdot (Q_U - Q_L) - Q_U$$ **Equation 0-8**

The transformation for Sacramento tributaries assumed the peak occurred half-way through the day for a time ratio of 0.5. The assumption results in an average peak flow value for unknown time ratios between the limiting cases of t_R equal to 1 or 0.

For two adjacent bins with the same flow rate, there is no method for conserving volume while adjusting the instantaneous point on the upper and lower bounds. Under those conditions, the instantaneous points at the upper and lower bounds equals the mean daily flow and creates a discontinuity in the estimated instantaneous flow record.

Flow Duration Bins

Flow duration values were developed for each unique upper bound, lower bound, and instantaneous discharge value. The nonexceedance probability equals the amount of time equal to or below each discharge divided by the total period of record plus 1 day. The additional day accounts for uncertainty in the empirical plotting position from using daily flow records.

The continuous empirical flow duration pattern was divided into 20 bins based on a sediment transport potential weighted volume of water. For an equivalent volume of water, lower flows transport less sediment than higher flows. A power relationship expressing sediment transport as a function of discharge can provide a rough approximation of relative transport rates. Bins were determined by first exponentially weighting each discharge and multiplying by the time to obtain a total weighted volume, Equation 0-9.

$$\sum V_w = \sum \left(Q^b\right) \cdot t \qquad \textbf{Equation 0-9}$$

Where,

V_w = exponentially weighted volume;

Q = discharge;

b = assumed sediment rating curve exponent; and

t = duration of flow at discharge Q.

The sum of the weighted volumes was then divided by the number of desired bins to determine the amount of weighted volume in each bin,

$$V_{w,n} = \frac{\sum V_w}{n} \qquad \textbf{Equation 0-10}$$

Where,

$V_{w,n}$ = weighted volume in each bin;

i = bin; and

n = number of bins.

The sediment rating exponent varies from site to size. A conservative value (under-predicts the nonlinear sediment transport behavior) of 2 was assumed for all gages for the purpose of dividing the flow duration curve into bins.

The representative flow for each weighted bin was also determined according to the sediment transport weighting method. Equation 0-11 computes the representative flow for each bin by dividing the exponentially weighted volume

$$Q_{r,i} = \left(\frac{V_{w,n}}{2 \cdot (t_{i+1} - t_i)} \right)^{1/b}$$ **Equation 0-11**

Where,

$Q_{r,i}$ = representative flow rate for bin i;

$V_{w,n}$ = weighted volume in each bin;

t = non-exceedance time (plotting position); and

b = assumed sediment rating curve exponent.

Weighting the representative flow for each bin better captures the sediment transport potential of each bin. However, the representative flow and the duration no longer results in the same annual volume of water as the gage record. Bins conserve annual volumes of sediment, not volumes of water.