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Navigability Potential of Washington Rivers and Streams Determined with Hydraulic Geometry and a Geographic Information System

Scientific Investigations Report 2009–5122

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

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

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

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Conversion Factors

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
inch (in.)	25.4	millimeter (mm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
mile, nautical (nmi)	1.852	kilometer (km)
yard (yd)	0.9144	meter (m)
	Volume	
cubic foot (ft^3)	0.02832	cubic meter (m^3)
cubic yard (yd^3)	0.7646	cubic meter (m^3)
cubic mile (mi^3)	4.168	cubic kilometer (km^3)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

Datum

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

Navigability Potential of Washington Rivers and Streams Determined with Hydraulic Geometry and a Geographic Information System

By Christopher S. Magirl and Theresa D. Olsen

Abstract

Using discharge and channel geometry measurements from U.S. Geological Survey streamflow-gaging stations and data from a geographic information system, regression relations were derived to predict river depth, top width, and bottom width as a function of mean annual discharge for rivers in the State of Washington. A new technique also was proposed to determine bottom width in channels, a parameter that has received relatively little attention in the geomorphology literature. These regression equations, when combined with estimates of mean annual discharge available in the National Hydrography Dataset, enabled the prediction of hydraulic geometry for any stream or river in the State of Washington.

Predictions of hydraulic geometry can then be compared to thresholds established by the Washington State Department of Natural Resources to determine navigability potential of rivers. Rivers with a mean annual discharge of 1,660 cubic feet per second or greater are “probably navigable” and rivers with a mean annual discharge of 360 cubic feet per second or less are “probably not navigable.” Variance in the dataset, however, leads to a relatively wide range of prediction intervals. For example, although the predicted hydraulic depth at a mean annual discharge of 1,660 cubic feet per second is 3.5 feet, 90-percent prediction intervals indicate that the actual hydraulic depth may range from 1.8 to 7.0 feet. This methodology does not determine navigability—a legal concept determined by federal common law—instead, this methodology is a tool for predicting channel depth, top width, and bottom width for rivers and streams in Washington.

Introduction

The Washington State Constitution (Article XVII, Section 1) asserts State

> “ownership to the beds and shores of all navigable waters in the state up to and including the line of ordinary high tide, in waters where the tide ebbs and flows, and up to and including the line of ordinary high water with the banks of all navigable rivers and lakes.”

In light of this article of the constitution, the Washington State Department of Natural Resources (DNR) needed a statewide methodology to assess the navigability potential of streams or rivers in the State of Washington. Although the question of navigability is ultimately decided by the courts, DNR developed thresholds of physical river-channel characteristics that predict the navigability potential of Washington rivers and streams (table 1). The thresholds in table 1 were determined for river flows equal to the mean annual discharge. Although other States assert similar ownership of navigable streams, DNR has found no other States that have thus far established a criterion or methodology to assess navigability potential (Michal Rechner, Washington State Department of Natural Resources, oral commun., 2008).

In order to determine the navigability potential of a stream or river in Washington using the thresholds in table 1, a statewide dataset of stream and river metrics was needed. Slope and discharge generally are available in geographic information system (GIS) datasets for stream segments throughout the State, but depth, top width, and bottom width are not available. In order to apply the DNR navigability thresholds to streams and rivers statewide, a method was needed to derive channel depth, top width, and bottom width from discharge for any given stream segment.

Downstream hydraulic geometry is a channel evaluation technique originally developed by Leopold and Maddock (1953) that relates width and depth in stream channels to discharge. Using U.S. Geological Survey (USGS) streamflow-gaging station data collected throughout the United States on rivers spanning several orders of magnitude of discharge, Leopold and Maddock (1953) found channel depth and width (as well as mean velocity and suspended-sediment load) correlated exponentially with discharge, Q, in the form

$$y = aQ^b \quad , \qquad (1)$$

where

y is the channel variable of interest, and

a and b are constants determined by regression.

The concept of hydraulic geometry has since become a widely applied tool in analyzing the hydrology and channel morphology of rivers worldwide (Ferguson, 1986) including rivers in the Pacific Northwest (Castro and Jackson, 2001). Although commonly applied to the alluvial channels, which have a tendency to alter and reshape their geometries (Huang and Nanson, 2000; Chew and Ashmore, 2001), exponential relations of depth and width to discharge have been found to apply to bedrock channels as well (Montgomery and Gran, 2001). Although the relations hold best for larger rivers and have some limitations for smaller, steep-gradient streams (Wohl, 2004), the technique of hydraulic geometry does, nonetheless, hold true for most rivers and streams.

By applying the principles of hydraulic geometry to empirical data from rivers and streams in Washington, a statewide relation between discharge and channel metrics can be derived. Applied to existing slope and discharge data within a GIS framework, these relations provide a methodology for deriving channel metrics and an assessment, with the DNR thresholds in table 1, of navigability potential for any stream or river in the State.

Purpose and Scope

This study, by applying principles of hydraulic geometry to statewide discharge and slope data within a GIS, develops a methodology to predict the physical characteristics of streams and rivers in the State of Washington. Confidence intervals of the predictions, based on the variance in the data, also are presented. The specific channel characteristics of interest (that is, channel depth, top width, bottom width, and channel slope) are compared to thresholds established by DNR (table 1) to produce a map and dataset of navigability potential for all streams and rivers in the State of Washington. These products will enable DNR to decide which rivers and streams may have navigability potential. The tools and methodology developed in this study do not predict or assert navigability. Instead, they predict the physical characteristics of a given river reach, which, in turn, can indicate the navigability potential of that reach.

Table 1. Thresholds of physical river-channel characteristics determined for river flows equal to the mean annual discharge that predicts the navigability potential of a stream or river reach in the State of Washington.

[Thresholds provided by the Washington State Department of Natural Resources (DNR). **Abbreviations**: <, less than; >, greater than; n/a, not applicable]

Channel characteristics	DNR Thresholds		
	Navigable		
	Probably not	May be depending on balance of factors	Probably
Mean depth, D_h (feet)	$D_h < 2$	$2 < D_h < 3.5$	$D_h > 3.5$
Top width, W_t (feet)	$W_t < 24$	$24 < W_t < 40$	$W_t > 40$
Bottom width, W_b (feet)	$W_b < 18$	n/a	$W_b > 18$
Gradient or slope, S (feet/foot)	$S > 0.0047$	$0.0019 < S < 0.0047$	$S < 0.0019$

Methods

Development of the methodology to predict channel geometry and navigability potential in rivers and streams in the State of Washington required assembling a GIS data source, collecting channel-geometry data, relating channel geometry to the GIS data, and assessing navigability potential.

GIS Data Source

The GIS flowline layer used in the study was the 1:100,000-scale National Hydrography Dataset (NHD) linked to the NHDPlus dataset, a hydrologically conditioned digital elevation model (DEM) with 30-m cell-sized resolution (U.S. Environmental Protection Agency, 2008). Specifically, the Region 17 flowlines, as a shapefile, represented the underlying drainage network that served as a surrogate for rivers and streams in Washington State (fig. 1). Where available, the flowline database contained the river or stream name. The specific attributes needed for this study came from the NHDPlus FlowlineAttributesFlow database file and included the slope (ft/ft) and the mean annual discharge, MAFLOWU (ft^3/s). The mean annual discharge stored in NHDPlus was determined using the unit runoff method, which uses catchment area and unit runoff data from regional USGS gaging stations to estimate discharge (Research Triangle Institute, 2001).

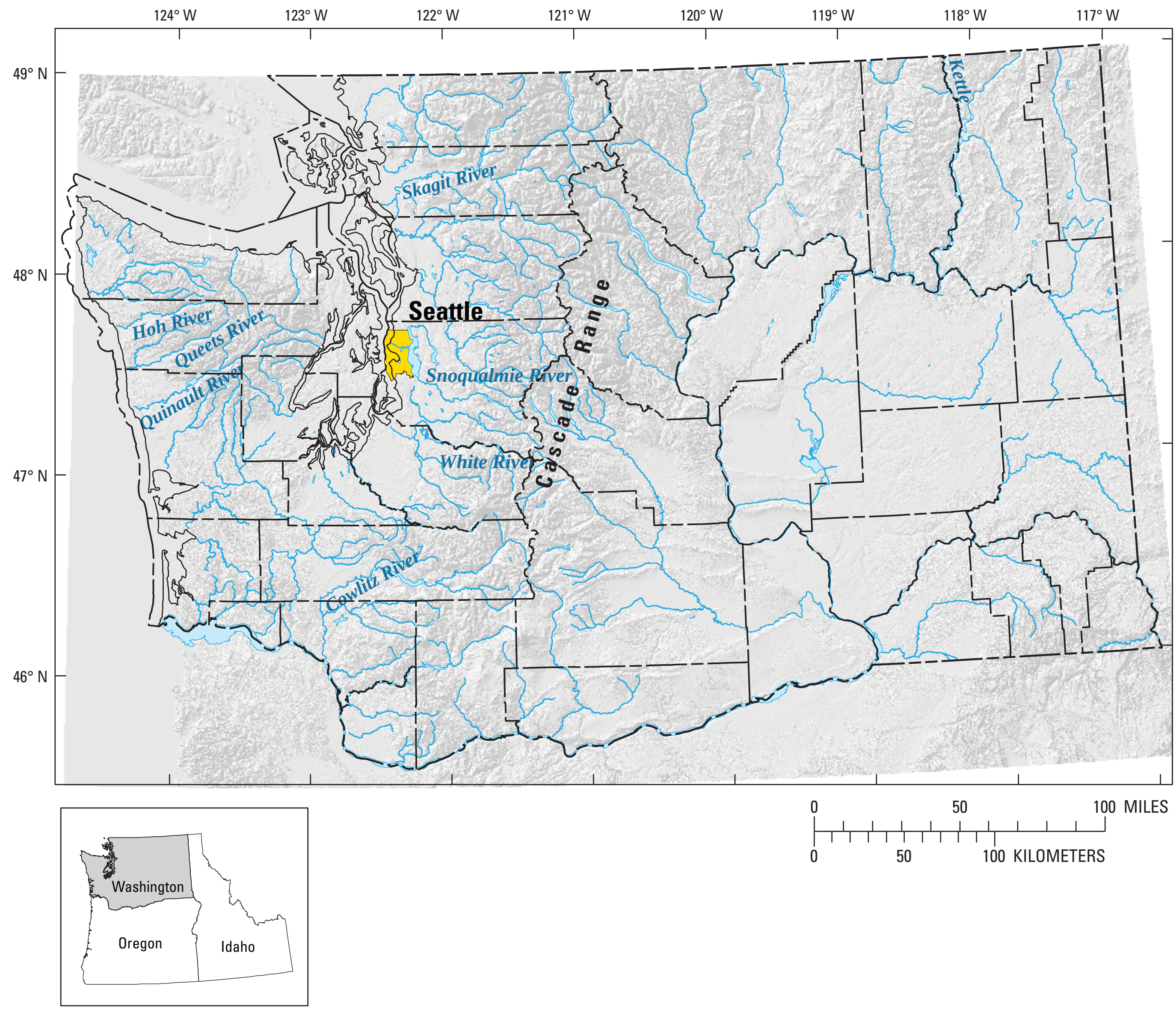

Figure 1. Large rivers in the State of Washington represented by the NHDPlus dataset.

Streamflow-Gaging Station Data

The USGS operates more than 200 active streamflow-gaging stations in the State of Washington. USGS staff periodically measures discharge at each gaging station to verify or update the stage-discharge relation. Discharge measurements require the collection of depth and water-velocity data at 20 or more locations along a transect perpendicular to the flowing water (Rantz and others, 1982). Velocity is measured using a current meter (for example, a Price AA), an acoustic Doppler velocimeter (ADV), or an acoustic Doppler current profiler (ADCP). Water depth is measured with either traditional mechanical sounding techniques or with the hydroacoustic instrumentation. These detailed depth and velocity data are stored at USGS field offices and in archives.

Detailed discharge measurements from gaging stations in Washington were collated for this study; the assembled data included the calculated discharge, the bathymetric profile across the transect, and the top width of the channel (appendix A). Owing to the focus of the study to evaluate channel characteristics at average discharge, only discharge measurements within ±10 percent of the mean annual discharge were evaluated. Although assembled discharge measurements spanned five orders of magnitude (from about 1 to 100,000 ft^3/s)—representing a reasonable sampling of all gaging stations in the State—most measurements were from streams with mean annual discharge between 100 and 10,000 ft^3/s; the discharge range thought to bound the DNR navigability thresholds. Inspection of the assembled data identified anomalies at some gaging stations. Six discharge measurements were discarded because they were located on small catchments (less than 4 mi^2) in an urbanized setting. These particular data appeared to be outliers relative to the larger dataset, probably as a result of engineering or channel alterations to these smaller streams. Another five discharge measurements were discarded because they were on streams dominated by seepage from a nearby reservoir. All assembled discharge measurements had been collected in the last 8 years.

From the discharge measurements, the hydraulic depth, D_h, at the cross section was calculated as the cross-sectional wetted area, A, divided by the top width, W_t (Chow, 1959):

$$D_h = \frac{A}{W_t} \quad . \qquad (2)$$

Hydraulic depth is essentially equivalent to the mean depth of the channel. The value of top width of the channel was taken directly from the discharge measurement and the cross-sectional area was calculated from the measured bathymetric profile.

Determining bottom width, W_b, was more complicated. Although calculating bottom width for a trapezoidal channel is relatively straight forward, calculating the bottom width of cross sections with irregular shapes can be ambiguous. For example, on a triangular cross section, bottom width could be determined as the width at one-half the maximum depth or as the width just upstream of the deepest part of the channel. Each choice, however, can introduce bias or artifacts that make geomorphic comparisons between disparate channels problematic. One approach considered for this study was to determine the bottom width at depths of 2.0 and 3.5 ft, the thresholds for hydraulic depth listed in table 1. However, channels with small to moderate discharge are often less than 2.0 or 3.5 ft deep and would thus have an indeterminate bottom width. Plotting these threshold-derived bottom widths against discharge also resulted in a non-linear relation with data truncation at small discharges. Because the focus of this study was to assess the navigability potential of a river or stream, we elected to calculate bottom width as the channel width at the hydraulic depth of the cross section. With this approach, a bottom-width value was determined for every cross section regardless of shape. The bottom width calculated in this manner correlated well with discharge using an exponential function, consistent with the methodology of hydraulic geometry (Leopold and Maddock, 1953). More importantly, this approach is independent of the navigability thresholds of table 1; therefore, thresholds can be changed or updated without affecting the regression model for the present study.

Regression Modeling

Using the selection criteria listed above, a total of 264 discharge measurements (representing channel measurements at 137 individual gaging stations) were assembled and analyzed for the study (fig. 2). As many as three replicate measurements were collected for each gaging station: 57 stations had one replicate, 33 stations had two replicates, and 47 stations had three replicates. Each discharge measurement represented an independent sampling of a particular gaging station with unique hydraulic and morphologic conditions—these conditions could differ greatly from year to year. Replicates of the same gaging station do not give a true parametric sampling of the entire dataset. The replicates, however, were distributed randomly throughout the dataset and did not bias the overall trends in the data (Tim Cohn, U.S. Geological Survey, oral commun., 2009). We chose to include replicates to increase the data available for the analysis rather than limit the analysis to fewer data. Although this approach does not bias the resulting regression model, it does result in overly optimistic confidence intervals (see section, "Calculating Confidence Intervals of Regression Models").

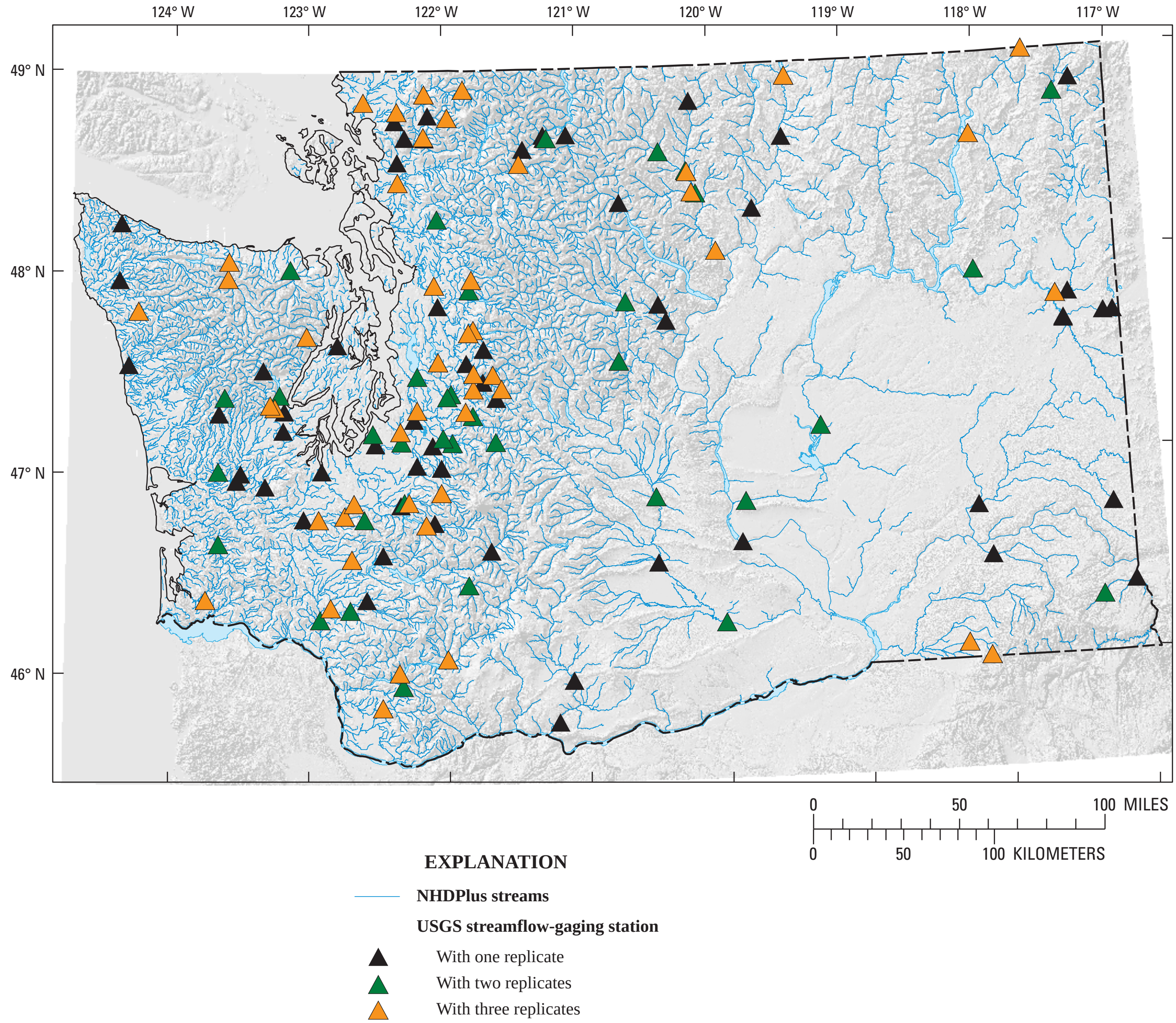

Figure 2. Rivers and streams with a mean annual discharge greater than 10 cubic feet per second and locations of discharge measurements in the State of Washington used in this study.

Consistent with the distribution of the gaging-station network in the State of Washington, 193 of the discharge measurements were collected west of the crest of the Cascade Range (Cascades) and 71 measurements were collected east of the crest. An evaluation of the regression relations showed no appreciable difference between data collected from the eastern and western sides of the Cascades. The depth and width of a river channel is a function of the discharge at that point in the river. Although discharge per unit area on the western side of the Cascade is different than the eastern side of the Cascades, the mean annual discharge of a given stream represents the integrated climatic influences of precipitation, catchment hydrology, and runoff. Therefore, when comparing channel shape to mean annual discharge (as opposed to drainage area, precipitation, or runoff), the regression relations are the same for the eastern and western sides of the State. Although precipitation patterns, catchment hydrology, and runoff may be different, a river with a mean annual discharge of 1,000 ft^3/s in the eastern side of the State will have similar channel geometry as a river with a mean annual discharge of 1,000 ft^3/s in the western side of the State—the morphologic response of the channel depends on the discharge in the river, not the drainage area or the depth of precipitation.

Hydraulic data from the gaging stations were spatially linked to the NHDPlus flowline network, thus relating hydraulic depth, top width, and bottom width to the NHDPlus estimate of mean annual discharge (MAFLOWU) and slope. Simple linear regression models, or ordinary least squares (Helsel and Hirsch, 1992), of the *log-log* transformations of D_h and MAFLOWU, W_t and MAFLOWU, and W_b and MAFLOWU were calculated. Those regression equations were then transformed back into real coordinate space giving equations relating D_h, W_t, and W_b to MAFLOWU in an exponential form (eq. 1).

Calculating Confidence Intervals of Regression Models

To evaluate the variance of the three regression models using ordinary least squares, 90-percent confidence intervals were calculated for each relation. Complete details for calculating confidence intervals are available in most statistics books (for example, Helsel and Hirsch, 1992); a brief overview of the techniques used for this study is presented here.

Given a population of *x-y* data, where x_i is the *i*th observation of the explanatory (or independent) variable and y_i is *i*th observation of the response (or dependent) variable, a linear equation

$$\hat{y} = b_0 + b_1 x_i \quad , \tag{3}$$

exists that minimizes the cumulative error between the estimate, $\hat{y}$, and the response variable, y_i. In equation (3), b_0 and b_1 are constants adjusted to minimize the estimate error. The error estimate, more appropriately termed the error sum of squares (*SSE*), is given by

$$SSE = \sum_{i=1}^{n} \left(y_i - \hat{y} \right)^2 \quad , \tag{4}$$

where *n* is the sample size of the dataset. In determining the ordinary least squares, a number of variance parameters are computed that are used to estimate the confidence intervals. Specifically, these parameters are the sums of the squares of *x* (SS_X),

$$SS_X = \sum_{i=1}^{n} \left(x_i - \bar{x} \right)^2 \quad , \tag{5}$$

the sums of the squares of *y* (SS_Y),

$$SS_Y = \sum_{i=1}^{n} \left(y_i - \bar{y} \right)^2 \quad , \tag{6}$$

and the sums of the *x-y* cross products (S_{XY}),

$$S_{XY} = \sum_{i=1}^{n} \left(x_i - \bar{x} \right)\left(y_i - \bar{y} \right) \quad , \tag{7}$$

where $\bar{x}$ and $\bar{y}$ are the means of the explanatory and response variables, respectively. Using equations (6) and (7), the standard error of the regression, *s*, can be determined with

$$s = \sqrt{\frac{\left(SS_Y - b_1 S_{XY} \right)}{\left(n - 2 \right)}} \quad . \tag{8}$$

Similarly, the coefficient of determination of the regression can be calculated with

$$R^2 = 1 - \frac{SSE}{SS_Y} \quad , \tag{9}$$

which is the fraction of variance explained by the regression.

The confidence interval, *CI* for the conditional mean of *y* at any value of *x* (represented by x_0) is then determined with the following:

$$CI = \hat{y} \pm t \bullet s \sqrt{\frac{1}{n} + \frac{\left(x_0 - \bar{x} \right)^2}{SS_X}} \quad , \tag{10}$$

where *t* is from the students' *t*-distribution having *n*-2 degrees of freedom with the probability of exceedance of $\alpha/2$ (Helsel and Hirsch, 1992). In this study, we calculated 90-percent confidence intervals, thus $\alpha = 0.90$ and $t = 1.65$. Equation (10) gives an estimate of the uncertainty with which the regression relation (eq. 3) represents the mean value of *y* at a given value of x_0. Thus, given a value of x_0, there is a 90-percent confidence that the actual mean of *y* is within the confidence intervals given by equation (10). But equation (10) does not give the uncertainty of the regression model to predict an individual value of *y* (as opposed to the mean values of *y*). To estimate the prediction interval, PI_α, or the uncertainty of the regression equation (3) to predict an individual value of *y*, the follow equation is used (Helsel and Hirsch, 1992):

$$PI = \hat{y} \pm t \bullet s \sqrt{1 + \frac{1}{n} + \frac{\left(x_0 - \bar{x} \right)^2}{SS_X}} \quad , \tag{11}$$

For the present study, using the determined regression models, there is a 90-percent confidence that the real value of *y* is within the limits defined in equation (11).

In analyzing the regression equations of D_h, W_t, and W_b versus MAFLOWU using equations (3)-(11), a number of assumptions about the dataset are made (Helsel and Hirsch, 1992): (1) *y* is linearly related to *x* (in this case, under a *log-log* transformation), (2) data used to fit the models are representative of the data of interest, (3) variance of the residuals is constant, (4) residuals are independent, and (5) residuals are normally distributed. Each of these assumptions generally are met for the data analysis in this study with the possible exception of assumption (2) (see section, "Results").

Navigability Potential

Combining the regression relations of hydraulic depth, top width, and bottom width versus discharge with the discharge and slope available in the NHDPlus dataset, maps of the navigability potential of streams and rivers in the State of Washington were constructed. Using the regression models, four statewide maps were generated showing the navigability potential of Washington rivers and streams based on the four channel characteristics.

Results

The collected channel-geometry data, combined with the GIS dataset, enabled the generation of regression relations between channel geometry and discharge as well as the construction of maps showing the navigability potential of Washington State rivers and streams.

Hydraulic Geometry Relations

The hydraulic depth data from the 264 discharge measurements plotted as a function of mean annual discharge from the NHDPlus dataset is shown in figure 3. The regression equation between hydraulic depth and mean annual discharge is:

$$D_h = 0.23Q^{0.37} \quad , \tag{12}$$

where Q is the mean annual discharge from the NHDPlus dataset (MAFLOWU). The coefficient of determination of the regression was $R^2 = 0.67$. The 90-percent confidence and prediction intervals also are shown in the figure;
the equation describing the 90-percent prediction intervals is

$$\log\left(PI_{D_h}\right) = 0.369\log Q - 0.646 \pm 0.297\sqrt{1.004 + \frac{\left(\log Q - 2.813\right)^2}{127.87}} \quad , \tag{13}$$

Using equation (12) and comparing the results to the thresholds listed in table 1, the predicted hydraulic depth is 3.5 ft for a discharge of 1,664 ft^3/s. Similarly, the predicted hydraulic depth is 2.0 ft for a discharge of 366 ft^3/s. By these measures, a river segment with a mean annual discharge, given by NHDPlus, greater than 1,660 ft^3/s would have a tendency toward being navigable although a stream or river less than 370 ft^3/s would probably not be navigable. The variance in the dataset, however, precludes precise predictions. For example, although a river with a mean annual discharge of 1,664 ft^3/s would have a predicted hydraulic depth of 3.5 ft, the 90-percent prediction intervals at that discharge indicated that the hydraulic depth could range from 1.8 to 7.0 ft.

The top width data plotted as a function of mean annual discharge is shown in figure 4. The regression equation between top width and mean annual discharge was

$$W_t = 4.85Q^{0.45} \quad . \tag{14}$$

The coefficient of determination of the regression was $R^2 = 0.82$. The equation describing the prediction intervals is

$$\log\left(PI_{W_t}\right) = 0.450\log Q + 0.686 \pm 0.247\sqrt{1.004 + \frac{\left(\log Q - 2.813\right)^2}{127.87}} \quad . \tag{15}$$

According to the regression equation, the predicted top width is 40 ft for a discharge of 109 ft^3/s and 24 ft for a discharge of 35 ft^3/s. In contrast to hydraulic depth, which required a large discharge to meet the navigability threshold, the navigability for the top width of a channel is achieved at a modest discharge. The variance in the top width dataset also has a wide range: A river with a mean annual discharge of 109 ft^3/s would have a prediction top width range (at 90-percent confidence) of 23 to 71 ft.

The bottom width data plotted as a function of mean annual discharge (fig. 5) where the regression equation between hydraulic depth and mean annual discharge is

$$W_b = 2.14Q^{0.46} \quad . \tag{16}$$

The coefficient of determination of the regression was $R^2 = 0.75$. The equation describing the 90-percent prediction intervals is

$$\log\left(PI_{W_b}\right) = 0.460\log Q + 0.330 \pm 0.303\sqrt{1.004 + \frac{\left(\log Q - 2.813\right)^2}{127.87}} \quad . \tag{17}$$

According to the regression equation, the predicted bottom width is 18 ft for a discharge of 102 ft^3/s. The trends in hydraulic geometry of bottom width mirror the trends in top width, with similar discharge values dictating navigability thresholds. The variance in the bottom width dataset shows a river with a mean annual discharge of 102 ft^3/s would have a predicted bottom width range (at 90-percent confidence) from 9 to 36 ft.

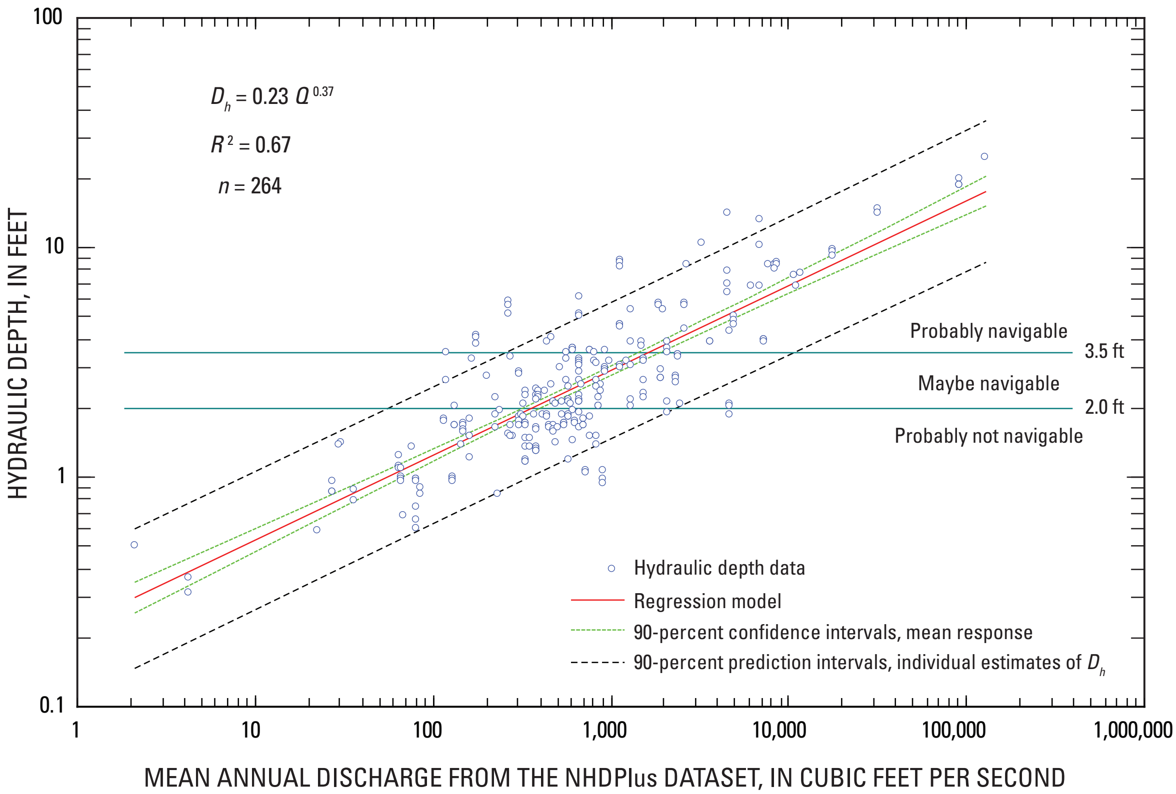

Figure 3. Hydraulic depth, D_h, and mean annual discharge, Q, determined from the NHDPlus dataset (MAFLOWU).Navigability thresholds are shown in table 1.

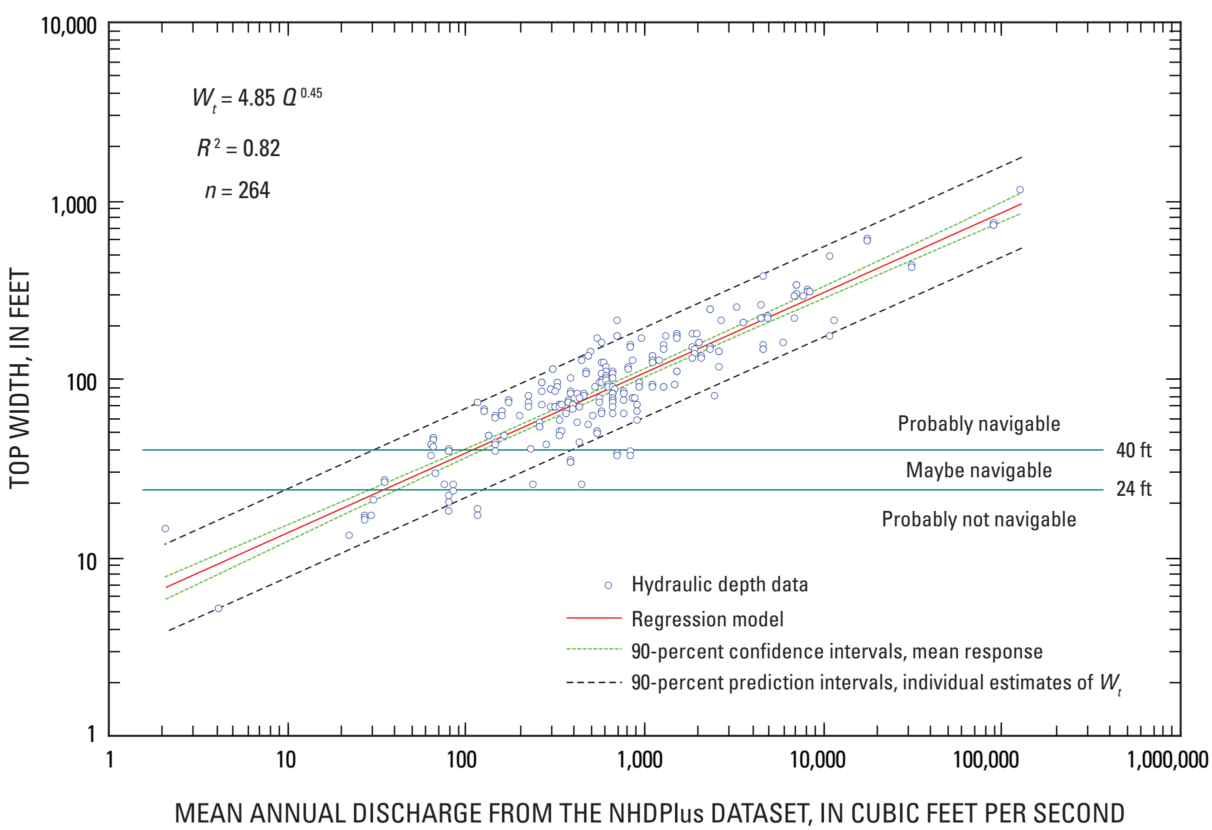

Figure 4. Top width, W_t, and mean annual discharge, Q, from the NHDPlus dataset (MAFLOWU). Navigability thresholds are shown in table 1.

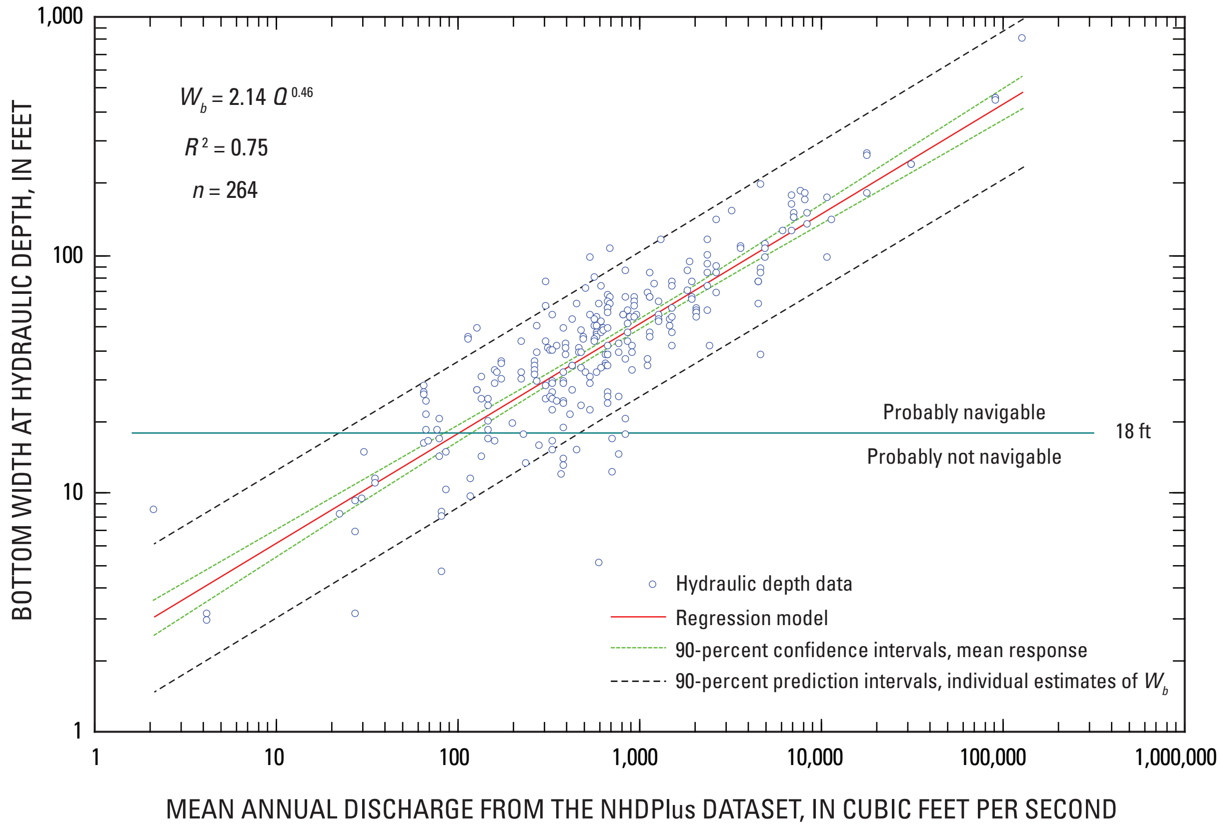

Figure 5. Bottom width, W_b, and mean annual discharge, Q, from the NHDPlus dataset (MAFLOWU). Navigability thresholds are shown in table 1.

Maps of Navigability Potential

Using the regression equations relating hydraulic depth, top width, and bottom width to MAFLOWU, all stream segments in the State of Washington in the NHDPlus dataset can be classified by their navigability potential per the thresholds in table 1. The navigability potential of all streams and rivers in Washington State based on the relation of hydraulic depth and MAFLOWU is shown in figure 6. To simplify the figure, only water courses with a MAFLOWU greater than 10 ft^3/s are displayed. In all, the maps display 21,798 individual stream segments; the length of individual stream segments varied but averaged 1.1 mi. Small streams and mountain rivers typically are classified “probably not navigable” and the larger rivers away from mountain fronts tend to be classified “probably navigable.”

Similar maps were constructed showing navigability potential based on top width (fig. 7) and bottom width (fig. 8). In both cases, river segments classified as probably navigable are widespread, extending high into mountains along most rivers and tributaries.

The maps show that, when considering all three hydraulic-geometry variables of interest, hydraulic depth is the limiting factor governing navigability potential for most rivers. Typically, if a river has a mean annual discharge to make it deep enough to meet the required navigability depth, then the river also usually is wide enough to be considered navigable. Streamflow-gaging station data indicate that 71 data points demonstrate adequate depths for navigation (> 3.5 ft). Of the 71 data points, 100 percent had top and bottom widths greater than the thresholds for navigability (40 and 18 ft, respectively). Of the 83 gaging-station data points with hydraulics depths between 2.0 and 3.5 ft, 98 percent had top widths greater than the navigability threshold and 95 percent had bottom widths greater than the navigability threshold.

The navigability potential map based on slope is ambiguous (fig. 9). The variability of river slope, as reported by the NHDPlus dataset, results in a navigability potential map with stream segments that alternate between “probably navigable” and “probably not navigable.” Moreover, there appears to be poor correlation between navigability potential based on slope reported by the NHDPlus dataset and navigability potential based on hydraulic depth or width. For example, the Hoh and Queets Rivers display navigability potential ranging from “probably navigable” to “navigability depends on balance of factors” throughout the lower reach, though both rivers probably are navigable. Many small streams with low gradient that appear to be potentially navigable (fig. 9), based on NHDPlus slope, are too shallow or narrow to support navigation. In general, slope as reported by the NHDPlus data appears to be an inconsistent indicator of navigability potential.

Based on the four maps generated in this study and the regression relations, hydraulic depth is the limiting factor deciding navigability potential. If the channel of interest meets the navigability threshold for hydraulic depth, the same channel quite likely meets the navigability criteria for top width and bottom width. Classification based on channel slope from the NHDPlus dataset generally is ambiguous and probably should not be used as a primary decision criterion for determining navigability potential.

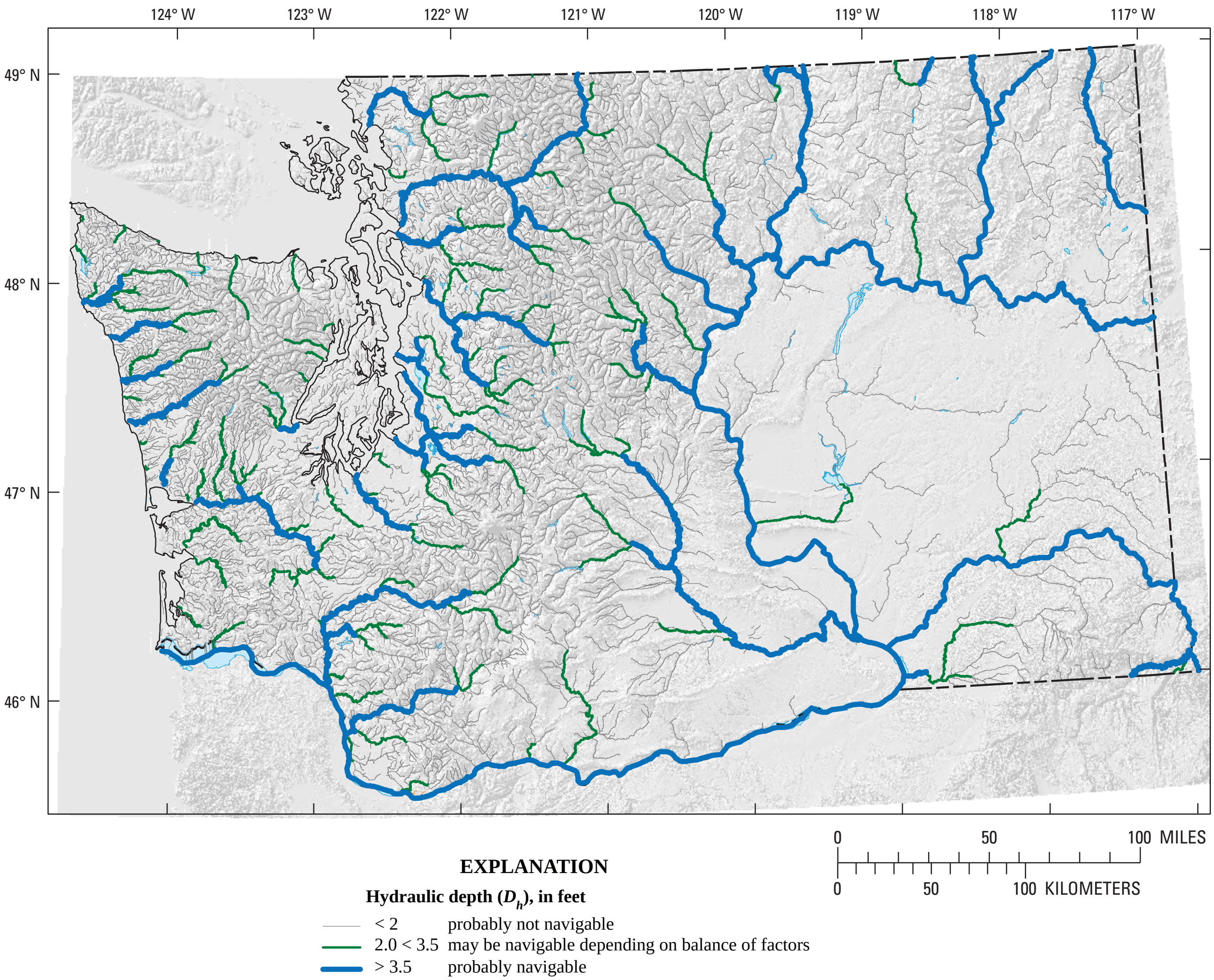

Figure 6. Navigability potential of rivers in State of Washington based on the regression prediction of hydraulic depth.

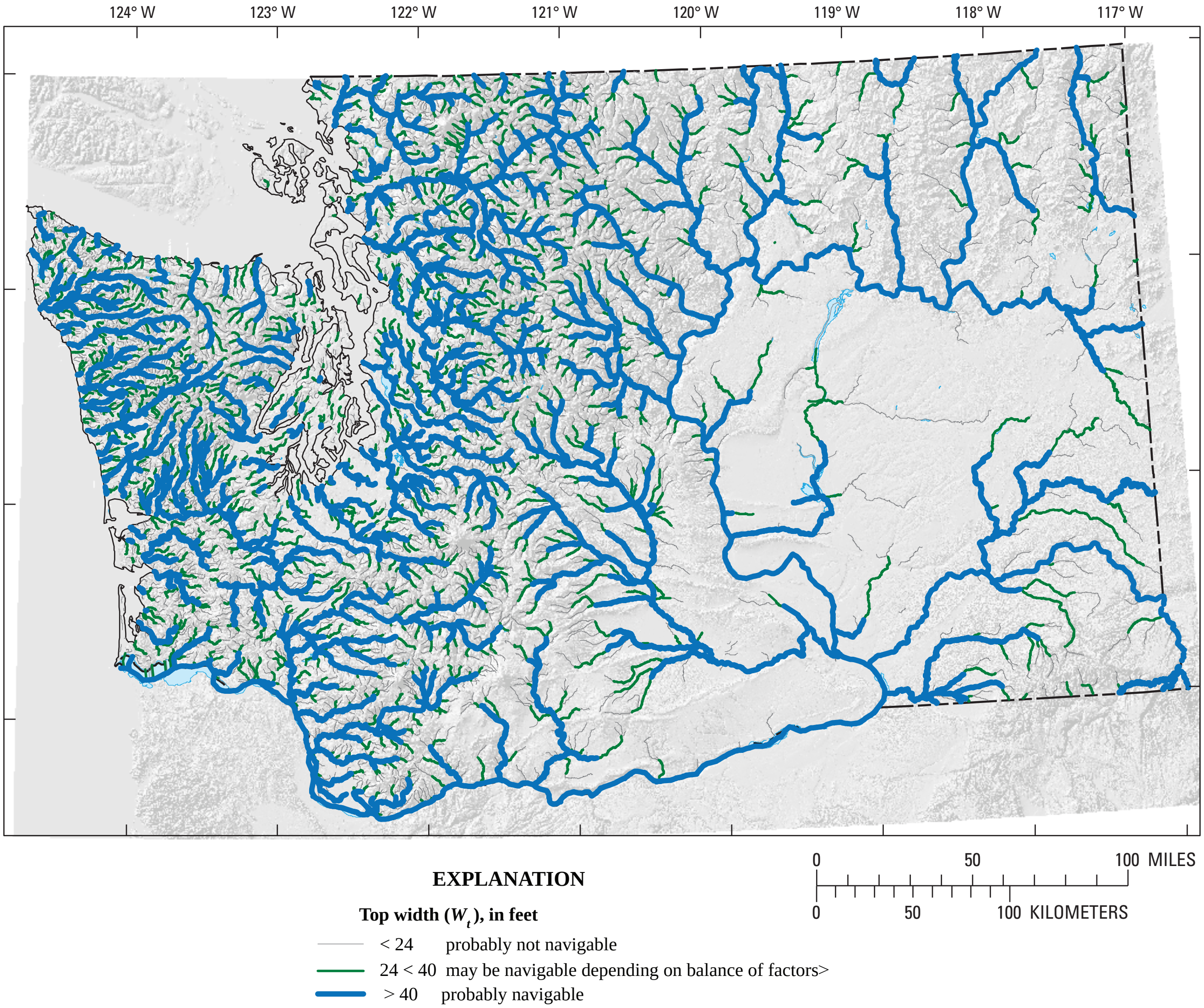

Figure 7. Navigability potential of rivers in the State of Washington based on the regression prediction of top width.

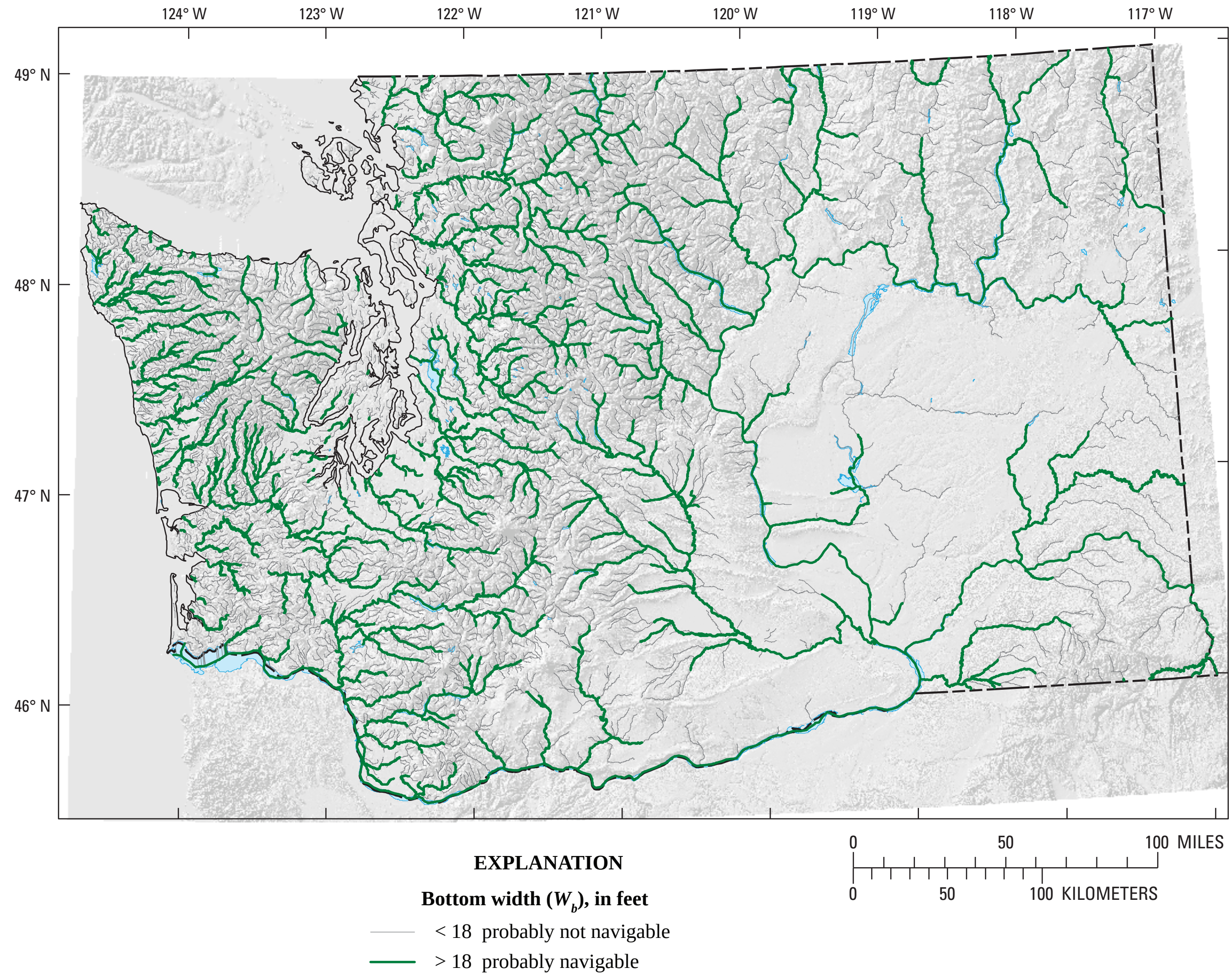

Figure 8. Navigability potential of rivers in the State of Washington based on the regression prediction of bottom width.

Comparison with Known Navigability

A few prominent rivers in the State of Washington have been either examined by the courts as to their navigability or have been classified by the DNR as being definitely navigable, probably navigable, or probably not navigable (Washington State Department of Natural Resources, 2004). Navigability potential, based on hydraulic depth, is in generally good agreement with the DNR provisional map. For example, the DNR map and the maps from this study show the Quinault, Queets, and Hoh Rivers as being navigable from the Pacific Ocean to near the boundary with Olympic National Park. The maps also agree along other major rivers including the Skagit, Snoqualmie, and Cowlitz Rivers. There were, however, some notable disagreements between the two maps. For example, although this study indicated the lower White River as being "probably navigable," the DNR map lists the White River from Pacific, Washington, to the confluence with the Puyallup River as being "probably not navigable." Based on a court case concerning a small section of the Kettle River in the State of Washington, DNR also assumed the entire river to be "probably not navigable," yet figure 6 classified most of the Kettle River as "probably navigable." Court evaluation of navigability in Washington considers many factors in addition to channel morphology. Thus, the navigability maps generated in this study can aid in assessing navigability potential; however, many factors ultimately dictate the legal threshold of navigability.

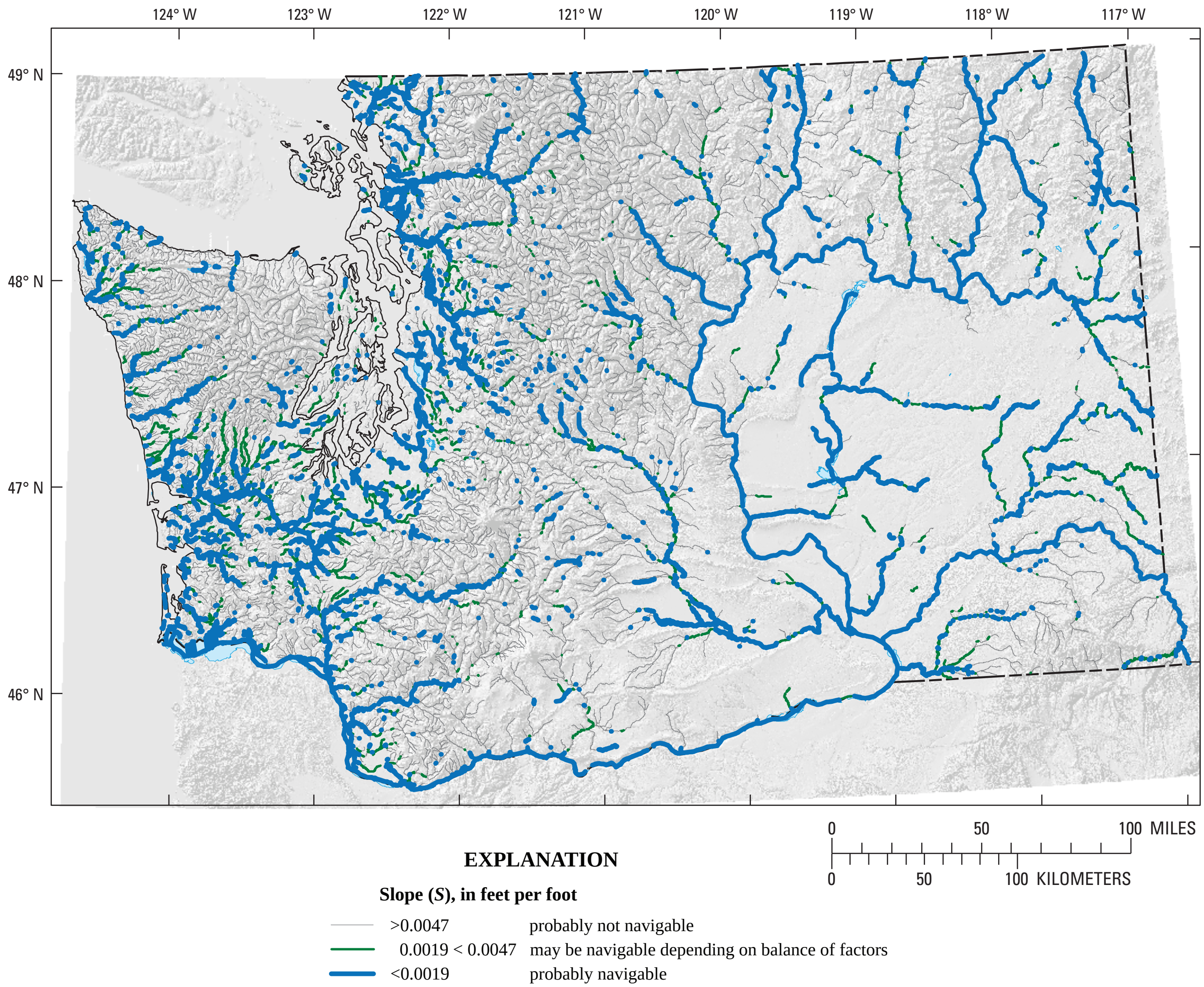

Figure 9. Navigability potential of rivers in the State of Washington based on the NHDPlus slope.

Bias in Hydraulic Geometry from Selected Locations of Gaging Stations

An assumption is made in the linear-regression analysis of this study that the channel characteristics at streamflow-gaging stations are representative of the entire river segment, but locations of streamflow-gaging stations are not selected randomly along rivers, rather the locations of gaging stations are selected on the basis of hydraulic conditions beneficial to discharge measurement. The location of gaging stations tend not to be situated on braided or distributary-channel systems; there is a bias in the selected locations of gaging stations toward straight reaches of single-channeled rivers with stable channel geometry producing stable stage-discharge relations.

When the hydraulic conditions at a streamflow-gaging station are controlled by a downstream boulder or cobble bar (typical of pool-riffle morphologies), the gaging station is considered to be influenced by section control. When the hydraulic conditions at a streamflow-gaging station are controlled by the roughness of the channel itself (typical of prismatic, alluvial channels), the gaging station is considered to be influenced by channel control. In developing the techniques of hydraulic geometry, Leopold and Maddock (1953) were aware that locations of gaging stations may not adequately represent averaged channel geometry. Leopold and Maddock (1953) attempted to choose data from gaging stations predominantly from channel-control sites.

In the present study, we made no attempt to differentiate between section control and channel control, nor did we preferentially select from channel-control gaging stations; the data in this study represent both control types. Thus, the methodology developed in the study is potentially biased due to the selection of locations for gaging stations. The potential bias would result in cross sections that are deeper than an average sampling taken at a random location along the river reach of interest. Moreover, section control tends to be most prevalent in smaller streams and mountain rivers, whereas channel control tends to dominate larger, alluvial rivers. The bias will be larger on rivers with smaller discharge, with the result that some of the smaller rivers could be classified as potentially navigable even though the average hydraulic depth throughout the river reach, incorporating the full pool-riffle sequence, might not actually meet the navigability threshold of table 1.

GIS Dataset Artifacts

The NHDPlus dataset is known to contain misrepresentations typical of hydrologic GIS databases. For example, the dataset has difficulties tracking the drainage network through lakes, sloughs, and estuaries; the NHDPlus flowline works best when representing rivers that are spatially well defined. In addition, the dataset has difficulties with distributary channels. Larger rivers often bifurcate into multiple channels that span the width of the floodplain. In these reaches, NHDPlus will show unique stream segments for individual channels, but estimates of mean annual discharge are assigned to only one of the channels. This results in a digital representation in which one channel is overloaded with discharge even though the other channels are underrepresented. In most cases, this representation does not affect classification outcomes as the overall discharge in the river follows the same general course, often reconnecting into a single channel downstream. Most secondary channels, where present, also are not visible at the final map scale.

One notable exception is the Skagit River. In the estuary delta, the Skagit River bifurcates into two large channels that independently empty into Puget Sound about 5 mi from each other. At moderate discharge, the northern channel carries about 60 percent of the total discharge and the southern channel carries about 40 percent, yet NHDPlus reports that all discharge follows the southern channel. NHDPlus shows the northern channel as a small regional flowline with little discharge. Therefore, both channels of the Skagit River are large and widely used for navigation in and out of Puget Sound; however, the final navigation maps published in this study show the northern channel as “probably not navigable,” an obvious error. Other errors or artifacts may be present in maps from this study, and all data should be verified with field observations or checked with independent data.

Data from NHDPlus were used ‘as is’ (U.S. Environmental Protection Agency, 2008), without corrections or improvements. Thus, the final navigability potential maps are as good as the accuracy of the underlying NHDPlus dataset.

Other Potential Error Sources and Caveats

As discussed in the section, “Methods,” multiple replicate data from some streamflow-gaging stations, although not biasing the regression, may result in confidence and prediction intervals that are narrower than if one replicate was used. To evaluate the effect of multiple replicates on the prediction interval, the dataset used in the linear regression of hydraulic depth to discharge was recalculated using only the first replicate from each gaging station (n = 137). The resulting 90-percent prediction intervals at a discharge of 1,660 ft^3/s, using just single replicates, ranged from 1.8 to 7.2 ft, or a total range of 5.4 ft—the comparable range of the 90-percent prediction interval at 1,660 ft^3/s using all 264 data points was 5.2 ft. Therefore, using all replicates (n = 264) in the analysis appeared to narrow the prediction intervals by about 4 percent.

The concepts of hydraulic geometry used in this study largely were derived from river data from self-forming alluvial rivers and streams. Many channels, however, actively are engineered in a way that restricts a channel’s natural trends. For example, bank stabilization or channel straightening often results in a river that is deeper and narrower than would otherwise occur. Similarly, channel maintenance (for example, dredging) often results in a channel that is deeper and narrower than it would be in a natural setting. Data used to develop the hydraulic geometry relations in this study were not segregated by degree of anthropogenic modification—this information generally was not available, would require much effort to obtain, and was beyond the scope of this investigation—but it is reasonable to say that a wide range in the degree of engineered alteration is represented by the channels included in the overall dataset. Considering these influences, the predictive equations in this study probably underpredict the hydraulic depth of a highly engineered channel and overpredict the hydraulic depth of a largely natural channel. Similarly, the equations probably also would overpredict the width of an engineered channel and underpredict the width of a natural channel.

Because depth was determined to be the limiting parameter of navigability potential, it is possible that for many channels on the threshold of navigability, the results from this study may indicate an average depth at or less than the navigability threshold when the actual depth, owing to anthropogenic effects, could be deeper. Again, a case-by-case investigation of the watercourse of interest is needed to fully assess the navigability potential.

Flow regulation and diversions from upstream dams also may affect the applicability of the methodology of this study. In some Washington rivers, large diversions for agricultural or municipal use can significantly lower the effective discharge in the channel. However, the mean annual discharge reported by NHDPlus is based on watershed and climatic parameters and generally does not consider flow regulation. Therefore, the NHDPlus discharge reported for more heavily used rivers may tend to overestimate the discharge in the channel. Again, case-by-case investigations of individual watercourses are needed to fully assess navigability potential.

Conclusions

Combining statewide discharge data and a GIS dataset with empirical techniques of hydraulic geometry, we developed a quantitative method for predicting the physical channel characteristics of any stream or river in the State of Washington. Using 264 discharge measurements at 137 U.S. Geological Survey streamflow-gaging stations distributed throughout the State, combined with the predicted mean annual discharge available in the NHDPlus dataset, allowed the prediction of hydraulic geometry with the following regression equations:

$$D_h = 0.23Q^{0.37} \ ,$$

$$W_t = 4.85Q^{0.45} \ ,$$

$$W_b = 2.14Q^{0.46} \ ,$$

where Q is the mean annual discharge from the NHDPlus dataset (MAFLOWU). Bottom width was defined as the channel width in the cross section at the hydraulic depth. Because the value of Q from the NHDPlus dataset integrates precipitation, drainage area, and runoff, the regression equations above are applicable statewide, that is, to regions east and west of the Cascade Range.

Comparing the regression relations developed in this study with the navigability thresholds provided by DNR, rivers with a mean annual discharge of 1,660 cubic feet per second or greater tend to be “probably navigable” and rivers with a discharge of 360 cubic feet per second or less are “probably not navigable.” Variance in the dataset, however, leads to relatively wide prediction intervals in the regressions. For example, although the predicted hydraulic depth at 1,660 cubic feet per second is 3.5 feet, the 90-percent prediction intervals indicate that the actual hydraulic depth in any given river could range from 1.8 to 7.0 feet.

Again, using Washington State Department of Natural Resources navigability thresholds, the predicted top width is 40 feet for a discharge of 109 cubic feet per second, and the predicted top width is 24 feet for a discharge of 35 cubic feet per second; navigability based on only the channel top width is achieved with modest discharge. Similarly, the bottom-width data showed that the predicted bottom width is 18 feet for a discharge of 102 cubic feet per second.

Of the three channel parameters analyzed in this study, hydraulic depth appeared to be the limiting parameter for defining navigability potential. Reach slope, as taken directly from the NHDPlus dataset, appeared to be a poor and inconsistent predictor of navigability potential.

There are a few caveats associated with the results of this study. First, the U.S. Geological Survey locates many of its streamflow-gaging stations just upstream of local hydraulic controls, which could result in predicted hydraulic depths greater than actual average stream depth. This bias would be most prevalent for smaller, mountainous rivers. Second, the NHDPlus dataset is known to contain some errors. No attempt was made in this study to correct these artifacts—the NHDPlus data were used ‘as is’. Finally, anthropogenic impacts on rivers and streams that alter channel geometry were not explicitly analyzed for this study. Instead, all rivers, whether free flowing or highly modified, were analyzed together as one population. As a general rule, highly affected rivers would tend to be deeper and narrower than their free-flowing counterparts.

Acknowledgments

Michal Rechner and Tim Strickler from the Washington State Department of Natural Resources provided technical support for the study. Sonja Lin (USGS) collected and collated gaging-station data from field offices throughout the State of Washington with the help of several field-office personnel. Morgan Keys (USGS) processed and cleaned the GIS database. Tim Cohn (USGS) provided valuable expertise and insight into the statistical analysis of this study. Peter Griffiths and Justin Ferris (both USGS) provided valuable reviews of the study report.

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Appendix A. Discharge Measurement Data Used in the Analysis.

[Measured discharge, hydraulic depth, top width, and bottom width were collected from U.S. Geological Survey streamflow-gaging stations in the State of Washington; MAFLOWU and Slope where collected for the given reach from the NHDPlus dataset. **Abbreviations:** ft^3/s, cubic foot per second; ft, foot; MAFLOWU, mean annual discharge; ft/ft, foot per foot]

Gaging station No.	Official name	Replicate	Measurement date (mm-dd-yy)	Measured discharge (ft^3/s)	Hydraulic depth (ft)	Top width (ft)	Bottom width (ft)	MAFLOWU (ft^3/s)	Slope (ft/ft)
12010000	Naselle River near Naselle	A	04-23-01	403	3.34	70	29	272	0.0039
		B	12-23-02	450	1.49	95	50	272	0.0039
		C	01-25-05	412	1.67	85	39	272	0.0039
12013500	Willapa River near Willapa	A	05-04-01	621	5.07	69	38	669	0.0001
		B	01-17-07	606	5.09	82	49	669	0.0001
12024000	South Fork Newaukum River near Onalaska	A	04-08-02	194	1.22	65	16	161	0.0055
		B	02-23-06	217	1.51	65	32	161	0.0055
		C	01-19-07	203	1.77	61	29	161	0.0055
12025700	Skookumchuck River near Vail	A	04-21-06	191	1.72	61	17	148	0.0165
		B	01-18-07	201	1.58	62	25	148	0.0165
12026150	Skookumchuck River below Bloody Run Creek, near Centralia	A	03-08-04	276	1.65	80	32	225	0.0019
		B	02-22-06	248	2.22	74	30	225	0.0019
		C	04-18-08	265	1.85	68	43	225	0.0019
12026400	Skookumchuck River near Bucoda	A	03-08-04	360	2.28	75	24	380	0.0014
		B	12-14-04	354	2.43	74	14	380	0.0014
		C	02-01-05	359	2.15	74	29	380	0.0014
12027500	Chehalis River near Grand Mound	A	02-28-06	2,920	10.36	247	151	3,280	0.0009
12031000	Chehalis River at Porter	A	01-17-03	4,430	14.09	259	62	4,570	0.0000
12035000	Satsop River near Satsop	A	04-07-08	1,990	5.35	177	76	1,970	0.0026
12035002	Chehalis River near Satsop	A	03-21-06	6,330	8.49	290	186	7,750	0.0003
12035400	Wynoochee River near Grisdale	A	05-17-02	484	2.88	113	60	306	0.0117
		B	02-06-03	470	2.83	112	77	306	0.0117
12036000	Wynoochee River above Save Creek, near Aberdeen	A	12-03-04	820	2.13	166	98	542	0.0036
12037400	Wynoochee River above Black Creek, near Montesano	A	05-18-01	1,150	3.07	132	67	1,140	0.0022
		B	05-25-05	1,210	2.98	132	84	1,140	0.0022
12040500	Queets River near Clearwater	A	06-11-08	4,140	4.36	372	197	4,700	0.0000
12041200	Hoh River at U.S. Highway 101, near Forks	A	07-25-07	2,680	2.56	246	116	2,360	0.0019
		B	01-17-08	2,730	2.71	243	58	2,360	0.0019
		C	06-11-08	2,600	2.73	242	73	2,360	0.0019
12043000	Calawah River near Forks	A	10-04-07	977	3.23	124	75	1,230	0.0035
12043300	Hoko River near Sekiu	A	10-04-07	405	2.52	82	41	468	0.0035
12044900	Elwha River above Lake Mills, near Port Angeles	A	06-01-05	1,280	2.47	154	36	845	0.0001
		B	05-04-06	1,270	3.13	150	86	845	0.0001
		C	06-27-07	1,500	2.62	150	66	845	0.0001
12045500	Elwha River at McDonald Bridge, near Port Angeles	A	07-06-06	1,570	8.16	91	66	1,140	0.0035
		B	12-19-07	1,360	8.68	90	45	1,140	0.0035
		C	05-07-08	1,460	8.87	91	47	1,140	0.0035
12048000	Dungeness River near Sequim	A	12-03-01	385	1.91	81	25	669	0.0098
		B	07-22-02	403	1.66	90	60	669	0.0098
12054000	Duckabush River near Brinnon	A	12-09-04	383	3.84	44	27	435	0.0186
		B	05-11-05	453	1.83	77	34	435	0.0186
		C	06-02-05	394	1.88	68	34	435	0.0186
12056500	North Fork Skokomish River below Staircase Rapids, near Hoodsport	A	04-08-05	547	1.64	139	72	505	0.0040
12058800	North Fork Skokomish River below Lower Cushman Dam, near Potlatch	A	10-01-07	57.6	1.39	37	18	834	0.0128
		B	12-11-07	56.5	1.49	39	20	834	0.0128

Appendix A. Discharge Measurement Data Used in the Analysis.—Continued

[Measured discharge, hydraulic depth, top width, and bottom width were collected from U.S. Geological Survey streamflow-gaging stations in the State of Washington; MAFLOWU and Slope where collected for the given reach from the NHDPlus dataset. **Abbreviations**: ft³/s, cubic foot per second; ft, foot; MAFLOWU, mean annual discharge; ft/ft, foot per foot]

Gaging station No.	Official name	Replicate	Measurement date (mm-dd-yy)	Measured discharge (ft³/s)	Hydraulic depth (ft)	Top width (ft)	Bottom width (ft)	MAFLOWU (ft³/s)	Slope (ft/ft)
12059500	North Fork Skokomish River near Potlatch	A	01-30-07	125	1.07	65	42	917	0.0021
		B	04-12-07	119	0.98	70	33	917	0.0021
		C	03-05-08	108	0.93	58	39	917	0.0021
12060500	South Fork Skokomish River near Union	A	04-22-02	700	1.69	213	106	700	0.0076
		B	02-14-06	677	1.78	170	65	700	0.0076
		C	03-28-06	754	1.68	172	62	700	0.0076
12061500	Skokomish River near Potlatch	A	03-28-06	1,170	2.69	175	93	1,900	0.0014
12069550	Big Beef Creek near Seabeck	A	02-04-08	37.0	0.67	29	17	69.2	0.0106
12076800	Goldsborough Creek above 7th Street Bridge, at Shelton	A	04-16-07	158	1.52	43	16	283	0.0044
12079000	Deschutes River near Rainier	A	10-22-03	244	2.39	67	42	398	0.0031
		B	01-23-07	262	2.26	70	40	398	0.0031
		C	04-15-08	267	2.24	71	38	398	0.0031
12080010	Deschutes River at E Street Bridge, at Tumwater	A	04-01-02	411	2.54	86	57	681	0.0067
12082500	Nisqually River near National	A	04-30-07	701	1.43	110	47	616	0.0109
12083000	Mineral Creek near Mineral	A	06-04-02	337	1.36	95	40	333	0.0056
		B	02-23-04	360	1.73	89	22	333	0.0056
		C	02-27-06	395	2.24	95	55	333	0.0056
12086500	Nisqually River at La Grande	A	02-07-07	1,310	3.88	153	54	1,287	0.0087
12087000	Mashel River near La Grande	A	05-28-02	211	1.60	84	32	387	0.0094
		B	03-08-06	230	1.63	82	49	387	0.0094
		C	05-30-08	199	1.30	100	29	387	0.0094
12090500	Clover Creek near TiIllicum	A	04-11-08	37.6	1.63	26	15	453	0.0042
12091500	Chambers Creek below Leach Creek, near Steilacoom	A	02-25-03	114	1.04	37	17	718	0.0059
		B	05-01-03	107	1.06	38	12	718	0.0059
12092000	Puyallup River near Electron	A	04-18-02	572	1.68	107	48	481	0.0137
		B	06-10-02	503	1.62	107	23	481	0.0137
		C	02-05-03	528	1.56	109	39	481	0.0137
12093500	Puyallup River near Orting	A	01-20-04	701	2.55	77	55	895	0.0083
12094000	Carbon River near Fairfax	A	03-09-07	414	1.85	64	12	373	0.0229
12095000	South Prairie Creek at South Prairie	A	12-08-06	219	2.10	55	34	484	0.0046
12097500	Greenwater River at Greenwater	A	05-19-03	203	1.49	51	24	351	0.0082
		B	04-26-07	203	1.36	70	41	351	0.0082
12098500	White River near Buckley	A	06-20-01	1,450	2.12	130	58	2,080	0.0162
		B	05-06-03	1,440	1.89	132	54	2,080	0.0162
12099600	Boise Creek at Buckley	A	12-01-06	35.2	0.90	25	15	86.5	0.0162
		B	04-01-08	32.4	0.84	23	10	86.5	0.0162
12100496	White River near Auburn	A	08-20-07	836	2.08	80	41	2,480	0.0042
12101500	Puyallup River at Puyallup	A	06-28-04	3,080	4.77	214	98	4,900	0.0006
		B	05-01-06	3,650	5.01	220	106	4,900	0.0006
		C	06-15-07	3,350	4.60	221	109	4,900	0.0006
12102075	Clarks Creek at Tacoma Road, near Puyallup	A	10-30-06	56.5	2.61	17	10	118	0.0022
		B	04-25-08	58.1	3.48	19	11	118	0.0022
12105900	Green River below Howard A. Hanson Reservoir	A	04-23-01	968	3.87	91	50	1,480	0.0112
		B	12-05-06	991	3.73	93	53	1,480	0.0112
12106700	Green River at Purification Plant, near Palmer	A	10-19-01	871	3.24	108	41	1,540	0.0072
		B	04-30-03	862	3.28	110	73	1,540	0.0072
		C	12-21-04	919	3.20	110	76	1,540	0.0072
12113000	Green River near Auburn	A	02-11-04	1,450	4.43	115	70	2,640	0.0012
		B	05-01-07	1,260	5.71	140	84	2,640	0.0012
		C	04-08-08	1,290	5.57	139	90	2,640	0.0012
12115000	Cedar River near Cedar Falls	A	11-29-01	231	1.85	85	41	318	0.0023
12116500	Cedar River at Cedar Falls	A	01-28-02	317	1.75	91	49	636	0.0263
		C	11-29-07	315	1.72	90	48	636	0.0263
12117500	Cedar River near Landsburg	A	02-23-06	666	2.96	95	66	942	0.0046
		B	02-14-07	622	2.85	94	63	942	0.0046
12117600	Cedar River below Diversion, near Landsburg	A	02-24-06	551	3.00	88	61	945	0.0063
		B	02-14-07	551	3.53	89	54	945	0.0063

Appendix A. Discharge Measurement Data Used in the Analysis.—Continued

[Measured discharge, hydraulic depth, top width, and bottom width were collected from U.S. Geological Survey streamflow-gaging stations in the State of Washington; MAFLOWU and Slope where collected for the given reach from the NHDPlus dataset. **Abbreviations**: ft^3/s, cubic foot per second; ft, foot; MAFLOWU, mean annual discharge; ft/ft, foot per foot]

Gaging station No.	Official name	Replicate	Measurement date (mm-dd-yy)	Measured discharge (ft^3/s)	Hydraulic depth (ft)	Top width (ft)	Bottom width (ft)	MAFLOWU (ft^3/s)	Slope (ft/ft)
12119000	Cedar River at Renton	A	03-10-04	668	2.03	88	53	1,290	0.0020
		B	02-24-06	687	2.18	89	64	1,290	0.0020
12121600	Issaquah Creek near mouth, near Issaquah	A	02-06-08	132	1.33	35	24	385	0.0032
		B	04-21-08	131	1.31	34	13	385	0.0032
		C	06-09-08	133	1.35	34	19	385	0.0032
12137800	Sultan River below Diversion Dam, near Sultan	A	05-24-05	203	1.73	51	22	545	0.0129
		B	03-29-07	183	1.70	49	29	545	0.0129
		C	05-02-07	182	1.69	51	31	545	0.0129
12138160	Sultan River below powerplant, near Sultan	A	06-27-02	758	3.27	107	59	672	0.0092
		B	06--06	683	3.18	109	68	672	0.0092
12141300	Middle Fork Snoqualmie River near Tanner	A	06-19-06	1,310	4.59	125	69	1,130	0.0128
		B	02-22-07	1,120	4.52	124	36	1,130	0.0128
		C	10-01-07	1,160	4.60	121	34	1,130	0.0128
12142000	North Fork Snoqualmie River near Snoqualmie Falls	A	10-11-07	530	4.04	80	39	468	0.0104
12143400	South Fork Snoqualmie River above Alice Creek, near Garcia	A	05-23-05	279	1.67	87	25	303	0.0024
		B	04-12-06	319	1.74	87	28	303	0.0024
		C	06-25-07	270	1.82	69	43	303	0.0024
12143600	South Fork Snoqualmie River at Edgewick	A	04-12-06	432	1.69	125	63	454	0.0025
12144000	South Fork Snoqualmie River at North Bend	A	04-13-06	558.	2.13	98	46	581	0.0026
		B	06-19-06	552	2.17	95	47	581	0.0026
		C	05-07-07	556	1.87	97	54	581	0.0026
12144500	Snoqualmie River near Snoqualmie	A	04-16-08	2,530	8.50	212	140	2,700	0.0631
12147500	North Fork Tolt River near Carnation	A	12-09-03	363	5.17	54	32	265	0.0386
		B	03-01-06	328	5.54	56	34	265	0.0386
		C	03-03-07	334	5.78	54	32	265	0.0386
12148500	Tolt River near Carnation	A	05-05-03	552	3.27	77	44	564	0.0103
		B	06-10-04	578	3.45	73	43	564	0.0103
		C	03-02-06	516	2.65	95	50	564	0.0103
12150800	Snohomish River near Monroe	A	06-28-06	10,000	7.53	489	175	10,900	0.0002
12155300	Pilchuck River near Snohomish	A	04-24-01	462	2.01	78	47	864	0.0021
		B	02-06-03	484	2.22	77	44	864	0.0021
		C	11-30-05	470	2.05	77	51	864	0.0021
12167000	North Fork Stillaguamish River near Arlington	A	04-12-06	1,890	5.67	130	71	1,860	0.0008
		B	05-04-07	2,030	5.59	148	86	1,860	0.0008
12175500	Thunder Creek near Newhalem	A	04-30-07	626	1.85	89	56	538	0.0143
12178000	Skagit River at Newhalem	A	12-07-07	4,580	6.80	160	125	6,120	0.0085
12178100	Newhalem Creek near Newhalem	A	04-27-06	171	1.60	44	20	147	0.0610
		B	11-19-07	189	1.69	43	18	147	0.0610
12179900	Bacon Creek below Oakes Creek, near Marblemount	A	11-19-07	388	1.53	94	36	268	0.0101
12181000	Skagit River at Marblemount	A	12-07-05	5,660	3.95	296	144	7,210	0.0019
		B	05-08-07	6,280	3.97	331	143	7,210	0.0019
		C	10-03-07	6,220	3.86	335	149	7,210	0.0019
12200500	Skagit River near Mount Vernon	A	01-04-06	17,500	9.88	600	257	17,900	0.0003
		B	05-08-07	16,700	9.08	597	263	17,900	0.0003
		C	02-12-08	17,500	9.67	587	180	17,900	0.0003
12201500	Samish River near Burlington	A	04-17-08	234	1.87	57	21	422	0.0027
12201960	Brannian Creek at South Bay Drive, near Wickersham	A	06-09-08	10.3	0.50	14	9	2.12	0.1113
12202300	Olsen Creek near Bellingham	A	01-02-08	10.5	0.59	13	8	22.6	0.0425
12205000	North Fork Nooksack River below Cascade Creek, near Glacier	A	07-22-04	827	2.24	83	34	661	0.0093
		B	10-13-05	760	2.12	77	35	661	0.0093
		C	07-31-06	734	3.07	63	38	661	0.0093
12206900	Racehorse Creek at North Fork Road, near Kendall	A	10-13-05	54.3	0.97	46	18	66.8	0.0633
		B	06-08-06	60.6	1.00	46	24	66.8	0.0633
		C	02-07-07	61.6	1.08	46	21	66.8	0.0633
12207750	Warm Creek near Welcome	A	03-31-04	28.9	0.97	16	9	27.4	0.1213
		B	05-05-05	26.4	0.85	16	7	27.4	0.1213
		C	06-22-06	27.4	0.86	17	3	27.4	0.1213

Appendix A. Discharge Measurement Data Used in the Analysis.—Continued

[Measured discharge, hydraulic depth, top width, and bottom width were collected from U.S. Geological Survey streamflow-gaging stations in the State of Washington; MAFLOWU and Slope where collected for the given reach from the NHDPlus dataset. **Abbreviations**: ft³/s, cubic foot per second; ft, foot; MAFLOWU, mean annual discharge; ft/ft, foot per foot]

Gaging station No.	Official name	Replicate	Measurement date (mm-dd-yy)	Measured discharge (ft^3/s)	Hydraulic depth (ft)	Top width (ft)	Bottom width (ft)	MAFLOWU (ft^3/s)	Slope (ft/ft)
12208000	Middle Fork Nooksack River near Deming	A	06-21-01	524	2.39	81	54	428	0.0243
12209000	South Fork Nooksack River near Wickersham	A	05-19-04	783	2.07	121	62	606	0.0009
12209490	Skookum Creek above Diversion, near Wickersham	A	02-08-07	140	2.02	48	14	135	0.0595
		B	05-16-07	140	1.68	48	25	135	0.0595
		C	06-04-07	144	1.66	48	31	135	0.0595
12210900	Anderson Creek at Smith Road, near Goshen	A	12-09-03	21.8	0.60	20	5	81.3	0.0095
		B	06-06-06	20.3	0.74	18	8	81.3	0.0095
		C	04-30-08	19.9	0.65	22	8	81.3	0.0095
12213100	Nooksack River at Ferndale	A	04-17-06	3,500	6.37	214	76	4,500	0.0004
		B	12-10-07	3,460	7.87	217	77	4,500	0.0004
		C	02-13-08	3,990	6.98	218	77	4,500	0.0004
12396500	Pend Oreille River below Box Canyon, near Ione	A	06-26-01	24,900	14.74	430	236	31,500	0.0132
		B	10-04-04	26,600	14.04	423	236	31,500	0.0132
12397100	Outlet Creek near Metaline Falls	A	11-30-05	79.5	0.97	41	28	66.5	0.0200
12399500	Columbia River at International boundary	A	05-05-04	95,600	18.82	728	453	90,900	0.0267
		B	09-28-05	94,500	18.78	724	445	90,900	0.0267
		C	04-12-07	109,000	19.98	734	452	90,900	0.0267
12409000	Colville River at Kettle Falls	A	02-27-03	302	1.69	51	29	337	0.0111
		B	04-14-04	300	1.47	48	16	337	0.0111
		C	12-05-07	326	2.34	58	29	337	0.0111
12419500	Spokane River above Liberty Bridge, near Otis Orchards	A	03-06-07	6,400	6.81	290	175	6,890	0.0019
12420500	Spokane River at Greenacres	A	6-01-05	4,830	10.16	215	124	6,890	0.0019
12422500	Spokane River at Spokane	A	03-06-07	6,820	13.18	287	161	6,960	0.0045
12424000	Hangman Creek at Spokane	A	04-07-03	235	2.73	62	20	201	0.0043
12431000	Little Spokane River at Dartford	A	06-18-08	307	3.30	48	32	166	0.0034
12431500	Little Spokane River near Dartford	A	05-17-06	598	4.10	75	30	176	0.0010
		B	03-02-07	607	4.03	75	35	176	0.0010
		C	06-18-08	578	3.81	74	35	176	0.0010
12433542	Blue Creek above Midnite Mine drainage, near Wellpinit	A	06-01-06	1.22	0.31	5	3	4.19	0.0409
		B	03-06-07	1.16	0.36	5	3	4.19	0.0409
12439500	Okanogan River at Oroville	A	02-09-00	654	1.87	144	87	4,6700	0.0005
		B	04-12-00	668	2.05	146	83	4,700	0.0005
		C	01-05-05	711	2.06	154	38	4,700	0.0005
12445000	Okanogan River near Tonasket	A	04-11-00	3,040	6.76	173	97	11,000	0.0009
12447200	Okanogan River at Malott	A	06-02-05	3,210	7.72	211	140	11,600	0.0003
12447383	Methow River above Goat Creek, near Mazama	A	07-10-03	461	1.20	160	80	576	0.0048
		B	03-31-04	468	1.84	122	53	576	0.0048
12447390	Andrews Creek near Mazama	A	07-13-06	28.6	1.38	17	9	29.9	0.0360
12448000	Chechuw River at Winthrop	A	06-07-01	354	1.84	63	14	771	0.0080
		B	07-14-06	373	1.51	76	25	771	0.0080
12448500	Methow River at Winthrop	A	04-05-00	1,270	2.66	177	47	1,540	0.0028
		B	04-07-04	1,170	2.21	174	60	1,540	0.0028
		C	01-26-05	1,090	2.34	167	54	1,540	0.0028
12448998	Twisp River near Twisp	A	06-22-05	245	1.15	71	25	335	0.0079
		B	04-20-06	235	1.18	69	27	335	0.0079
		C	07-14-06	251	1.16	72	15	335	0.0079
12449500	Methow River at Twisp	A	06-14-05	1,440	2.94	138	66	1,940	0.0031
		B	07-13-06	1,460	2.72	143	64	1,940	0.0031
12449950	Methow River near Pateros	A	04-04-00	1,490	3.31	150	91	2,390	0.0065
		B	03-31-04	1,530	3.44	149	99	2,390	0.0065
		C	01-27-05	1,470	3.40	143	84	2,390	0.0065
12451000	Stehekin River at Stehekin	A	04-19-07	1,510	5.30	146	55	1,310	0.0023
12452800	Entiat River near Ardenvoir	A	06-21-05	369	2.97	61	32.	514	0.0019
12452890	Mad River at Ardenvoir	A	03-30-06	85.3	0.84	40	18	233	0.0182
12456500	Chiwawa River near Plain	A	04-06-00	537	2.16	75	26	674	0.0083
		B	06-22-05	561	2.13	72	24	674	0.0083

Appendix A. Discharge Measurement Data Used in the Analysis.—Continued

[Measured discharge, hydraulic depth, top width, and bottom width were collected from U.S. Geological Survey streamflow-gaging stations in the State of Washington; MAFLOWU and Slope where collected for the given reach from the NHDPlus dataset. **Abbreviations:** ft^3/s, cubic foot per second; ft, foot; MAFLOWU, mean annual discharge; ft/ft, foot per foot]

Gaging station No.	Official name	Replicate	Measurement date (mm-dd-yy)	Measured discharge (ft^3/s)	Hydraulic depth (ft)	Top width (ft)	Bottom width (ft)	MAFLOWU (ft^3/s)	Slope (ft/ft)
12458000	Icicle Creek above Snow Creek, near Leavenworth	A	04-15-00	638	3.60	82	42	776	0.0406
		B	04-11-02	590	3.56	84	39	776	0.0406
12467000	Crab Creek near Moses Lake	A	08-30-07	69.3	1.80	74	45	116	0.0014
		B	10-02-07	61.5	1.74	74	44	116	0.0014
12472600	Crab Creek near Beverly	A	04-08-07	203	1.82	65	32	579	0.0014
		B	08-13-07	198	2.19	63	46	579	0.0014
12472800	Columbia River below Priest Rapids Dam	A	03-15-07	97,000	24.55	1,140	813	129,000	0.0006
12484500	Yakima River at Umantum	A	04-04-06	2,420	3.89	203	109	3,600	0.0019
		B	06-20-07	2,460	3.87	202	106	3,600	0.0019
12502500	Ahtanum Creek at Union Gap	A	04-20-07	82.6	1.97	25	13	238	0.0035
12508990	Yakima River at Mabton	A	03-03-06	3,020	8.50	318	181	8,280	0.0002
		B	06-28-06	3,200	8.11	306	169	8,280	0.0002
13334450	Asotin Creek below confluence, near Asotin	A	12-11-07	48.3	0.80	26	11	35.9	0.0187
		B	07-07-08	48.8	0.88	27	11	35.9	0.0187
13335050	Asotin Creek at Asotin	A	02-14-08	87.7	1.35	26	18	76.6	0.0088
13344500	Tucannon River near Starbuck	A	05-23-07	164	1.39	39	23	147	0.0069
13348000	South Fork Palouse River at Pullman	A	04-03-07	38.9	1.42	21	15	30.5	0.0046
13351000	Palouse River at Hooper	A	04-19-04	544	6.15	101	64	673	0.0030
14013000	Mill Creek near Walla Walla	A	12-21-06	93.2	0.97	40	20	80.6	0.0161
		B	04-12-07	97	0.97	39	14	80.6	0.0161
		C	04-09-08	100	0.98	39	17	80.6	0.0161
14015000	Mill Creek at Walla Walla	A	04-27-06	73.7	0.97	65	27	130	0.0129
		B	12-21-06	81.6	1.00	66	49	130	0.0129
		C	04-11-07	77.2	0.96	65	27	130	0.0129
14111400	Klickitat River below Summit Creek, near Glenwood	A	01-24-07	1,260	2.37	126	58	879	0.0058
14113000	Klickitat River near Pitt	A	01-24-07	1,640	3.07	173	115	1,320	0.0050
14216500	Muddy River below Clear Creek, near Cougar	A	02-01-05	848	3.12	81	34	674	0.0087
		B	04-04-06	931	2.85	81	41	674	0.0087
		C	04-25-07	788	2.64	81	38	674	0.0087
14219000	Canyon Creek near Amboy	A	12-01-06	416	1.84	68	25	323	0.0204
		B	02-22-08	432	2.06	68	40	323	0.0204
14219800	Speelyai Creek near Cougar	A	04-12-06	91.2	1.23	37	16.	65.0	0.0189
		B	11-30-06	100	1.10	43	26	65.0	0.0189
		C	04-10-07	101	1.09	43	27	65.0	0.0189
14222500	East Fork Lewis River near Heisson	A	05-18-00	676	3.62	98	33	623	0.0079
		B	05-25-05	742	3.60	101	52	623	0.0079
		C	04-13-06	664	3.59	102	73	623	0.0079
14226500	Cowlitz River at Packwood	A	06-25-07	1,500	3.20	169	56	986	0.0036
14231900	Cispus River above Yellowjacket Creek, near Randle	A	12-04-01	984	3.47	111	56	821	0.0051
		B	05-20-03	984	3.17	116	56	821	0.0051
14236200	Tilton River above Bear Canyon Creek, near Cinebar	A	02-23-04	805	2.49	106	50	585	0.0049
14240525	North Fork Toutle River below sediment retention structure near Kid Valley	A	11-05-06	731	1.96	114	5	609	0.0061
14241500	South Fork Toutle River at Toutle	A	03-28-06	610	2.07	135	45	492	0.0036
		B	12-04-06	570	1.42	132	44	492	0.0036
14242580	Toutle River at Tower Road, near Silver Lake	A	03-06-06	2,040	3.91	159	59	2,070	0.0029
		B	05-25-06	1,910	3.63	157	57	2,070	0.0029
		C	12-04-06	2,040	3.45	159	57	2,070	0.0029
14243000	Cowlitz River at Castle Rock	A	02-01-07	9,470	8.60	307	150	8,555	0.0009
		B	03-07-08	8,810	8.44	307	133	8,555	0.0009

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