Prepared in cooperation with the
Idaho Department of Fish and Game and the
Bonneville Power Administration

Simulation of Hydraulic Characteristics in the White Sturgeon Spawning Habitat of the Kootenai River near Bonners Ferry, Idaho

Scientific Investigations Report 2005–5110

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

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Gale A. Norton, Secretary

U.S. Geological Survey
Charles G. Groat, Director

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Conversion Factors

Multiply	By	To obtain
cubic foot per second (ft^3/s)	0.02832	cubic meter per second
foot (ft)	0.3048	meter
foot per mile (ft/mi)	0.1894	meter per kilometer
foot per second (ft/s)	0.3048	meter per second
mile (mi)	1.609	kilometer
square mile (mi^2)	2.590	square kilometer

Datums

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

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

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Simulation of Hydraulic Characteristics in the White Sturgeon Spawning Habitat of the Kootenai River near Bonners Ferry, Idaho

By Charles Berenbrock

Abstract

Hydraulic characterization of the Kootenai River, especially in the white sturgeon spawning habitat reach, is needed by the Kootenai River White Sturgeon Recovery Team to promote hydraulic conditions that improve spawning conditions for the white sturgeon (*Acipenser transmontanus*) in the Kootenai River. The decreasing population and spawning failure of white sturgeon has led to much concern. Few wild juvenile sturgeons are found in the river today. Determining the location of the transition between backwater and free-flowing water in the Kootenai River is a primary focus for biologists who believe that hydraulic changes at the transition affect the location where the sturgeon choose to spawn. The Kootenai River begins in British Columbia, Canada, and flows through Montana, Idaho, and back into British Columbia. The 65.6-mile reach of the Kootenai River in Idaho was studied. The study area encompasses the white sturgeon spawning reach that has been designated as a critical habitat.

A one-dimensional hydraulic-flow model of the study reach was developed, calibrated, and used to develop relations between hydraulic characteristics and water-surface elevation, discharge, velocity, and backwater extent. The model used 164 cross sections, most of which came from a previous river survey conducted in 2002–03. The model was calibrated to water-surface elevations at specific discharges at five gaging stations. Calibrated water-surface elevations ranged from about 1,743 to about 1,759 feet, and discharges used in calibration ranged from 5,000 to 47,500 cubic feet per second. Model calibration was considered acceptable when the difference between measured and simulated water-surface elevations was ±0.15 foot or less. Measured and simulated average velocities also were compared. These comparisons indicated agreement between measured and simulated values.

The location of the transition between backwater and free-flowing water was determined using the calibrated model. The model was used to simulate hydraulic characteristics for a range of water-surface elevations from 1,741 to 1,762 feet and discharges from 4,000 to 75,000 cubic feet per second. These simulated hydraulic characteristics were used to develop a three-parameter relation—discharge in the study reach, water-surface elevation at Kootenai River at Porthill gaging station (12322000), and the location of the transition between backwater and free-flowing water. Simulated hydraulic characteristics produced backwater locations ranging from river mile (RM) 105.6 (Porthill) to RM 158 (near Crossport), a span of about 52 miles. However, backwater locations from measured data ranged primarily from RM 152 to RM 157, a 5-mile span. The average backwater location from measured data was at about RM 154.

Three-parameter relations also were developed for determining the amount of discharge in the Shorty Island side channel and average velocity at selected cross sections in the study reach. Simulated discharge for the side channel relative to measured data ranged from 0 to about 5,500 cubic feet per second, and simulated average velocity relative to measured data ranged from 0 to about 3.5 feet per second. Relations using other hydraulic, sediment/incipient motion, ecological, and biological characteristics also could be developed.

The relations also can be used in real time by accessing data from the Web. Discharge and stage data for two gaging stations, Tribal Hatchery (12310100) and Porthill (12322500), are available from the Idaho U.S. Geological Survey web page (URL: http://waterdata.usgs.gov/id/nwis/current/?type=flow). Because the coordinate axes of the three-parameter relations use discharge from the Tribal Hatchery gaging station and water-surface elevation from the Porthill gaging station, the location of the transition between backwater and free-flowing water can be determined for current conditions using the real-time data. Similarly, discharge in the Shorty Island side channel and (or) average velocity at selected cross sections also can be determined for current conditions.

Introduction

The Kootenai River is an International river that originates in British Columbia and flows through Montana and Idaho and then back into British Columbia where it joins the Columbia River (fig. 1). The river has undergone many physical changes in the last century resulting from the drainage of wetlands; construction of dikes along the river's corridor from Bonners Ferry, Idaho, to Kootenay Lake, British Columbia; construction of dikes along the river's corridor near Troy and Libby, Montana; construction and operation of Libby Dam near Libby, Montana; and elevation control of Kootenay Lake by Corra Lynn Dam, British Columbia. Streamflow has been significantly altered because of the operation of Libby Dam (Barton, 2004), which may negatively influence spawning of selected resident fish species. One of the resident fish populations, the white sturgeon (*Acipenser transmontanus*), in the river have decreased substantially since the construction of Libby Dam in 1972. The Kootenai River white sturgeon has been isolated from other sturgeon in the Columbia River Basin by natural barriers for more than 10,000 years (Northcote, 1973). The last white sturgeon spawning event that recruited juveniles in the Kootenai River occurred in late spring of 1974. In 1994, the Kootenai River white sturgeon was listed as a Federal endangered species, and the existing catch and release fishery was closed. Today, few wild juvenile sturgeons are found in the river.

Peak flows in the Kootenai River have substantially decreased since the construction and operation of Libby Dam. Prior to the dam, natural average peak springtime runoff was about 80,000 ft^3/s, whereas, post-dam peak runoff during the mid- and late-1970s through the early 1990s averaged less than 10,000 ft^3/s. This decrease is suspected of being the major factor in the decrease of successful white sturgeon spawning events and, thus, the decreased population of wild sturgeon in the Kootenai River. As part of the recovery plan for the Kootenai River population of white sturgeon (U.S. Fish and Wildlife Service, 1999), spring flows were increased beginning in 1994, through managed releases at Libby Dam to about 25,000 ft^3/s in an attempt to re-create historical peak flows and enhance spawning conditions for white sturgeon. However, these augmented flows are still substantially less than typical pre-dam spring flows.

Post-dam changes of the river system also have altered the variability and magnitude of water-surface elevations in Kootenay Lake (fig. 1), to which the river discharges approximately at river mile (RM) 110, downstream of the sturgeon spawning reach. The river is in variable backwater from Kootenay Lake to the Bonners Ferry area, resulting in low-velocity conditions in the white sturgeon spawning habitat. The location of the transition between backwater and free-flowing water near Bonners Ferry varies in response to changing water-surface elevations in Kootenay Lake and water releases from Libby Dam coupled with tributary inflows downstream of the dam. Kootenay Lake levels typically are at a maximum after spring runoff and at a minimum during the autumn and winter months. White sturgeon may be reacting to hydraulic conditions caused by the changes in Kootenay Lake levels and flows in the river by seeking areas of suitable velocities for spawning. Kootenay Lake levels generally are lower now than during the pre-Libby Dam period causing the location of the transition between backwater and free-flowing water to extend not as far upstream; and sturgeon may be finding the proper velocities over inferior spawning habitat.

Ensuring the long-term future of the Kootenai River white sturgeon is of concern and contention among biologists, ecologists, water managers, engineers, and other interested segments of the population. This concern has spurred a greater interest in finding ways to promote recruitment of the sturgeon. In 1997, the Kootenai River White Sturgeon Recovery Team (KRWSRT) was formed under the provision of the Endangered Species Act of 1974 to develop and implement a recovery plan (Duke and others, 1999). KRWSRT is comprised of International multi-government agencies, universities, and consultants. Projects initiated by KRWSRT will provide information to answer complex recovery and management questions and produce tools necessary to implement and manage the water resources in the Kootenai River.

The U.S. Geological Survey (USGS) in cooperation with the Idaho Department of Fish and Game, a KRWSRT member, developed a hydraulic-flow model to improve understanding of hydraulic characteristics and to predict the location of the transition between backwater and free-flowing water (backwater extent) in the white sturgeon spawning reach.

A one-dimensional hydraulic-flow model of the river incorporating the white sturgeon spawning habitat was developed. This hydraulic-flow model encompasses the reach (65.6 mi) from Leonia to Porthill, Idaho.

In support of this model and others, about 400 bathymetric cross sections and longitudinal profiles from Libby Dam, Montana, to Kootenay Lake, British Columbia, Canada, were measured in 2002–03 (Moran and Berenbrock, 2003; Barton and others, 2004). Spacing between the cross sections ranged from 100 ft in the valley flat near Deep Creek and Shorty Island to as much as 1 mi in other areas.

Insights gained from numerical models are critical to the assessment and evaluation of possible remedies to improve spawning success. Relations from the hydraulic model can be incorporated into biological and ecological models of the Kootenai River to evaluate and assess the effects of hydraulic characteristics on white sturgeon spawning.

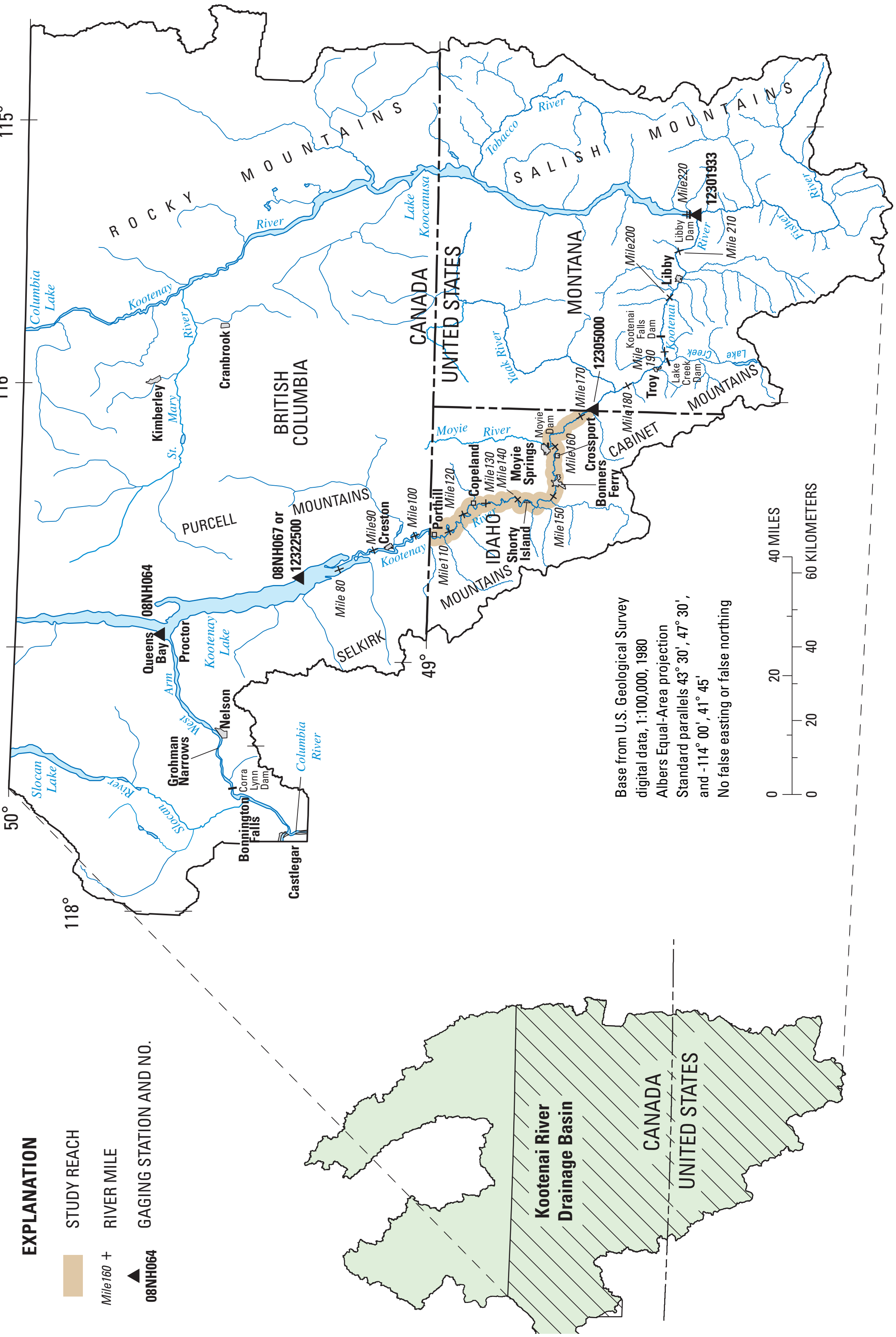
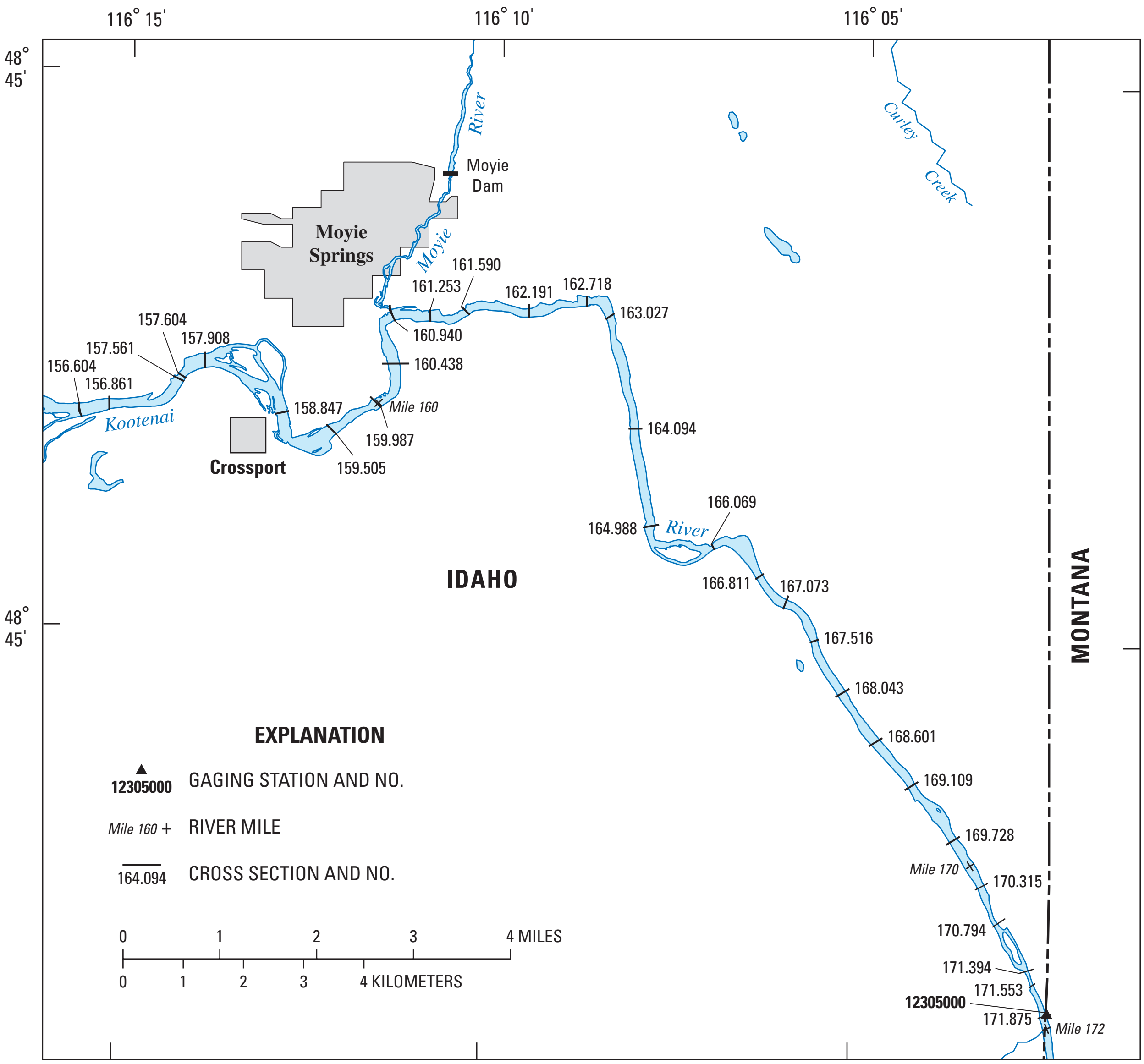


Figure 1. Location of the study reach, river miles, and Kootenai River drainage basin, Idaho, Montana, and British Columbia, Canada.

Purpose and Scope

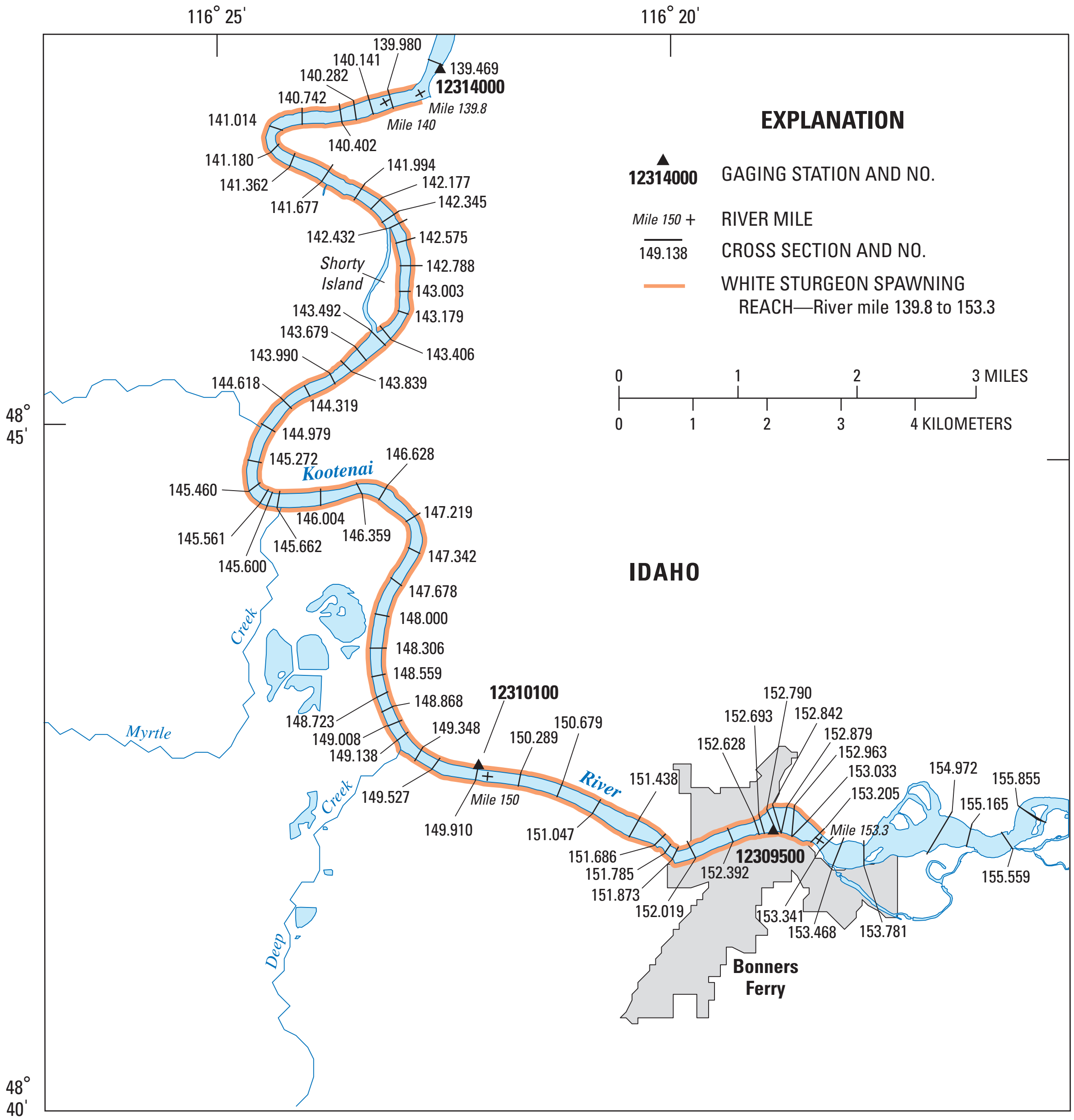
The purpose of this report is to document a model of the hydraulic characteristics of the white sturgeon spawning habitat of the Kootenai River near Bonners Ferry, Idaho. Specifically, determining the location of the transition between backwater and free-flowing water is of primary interest because biologists believe that the sturgeon sense the decreased velocities in backwater areas and will relocate to areas with preferred velocities to spawn (Paragamian and Kruse, 2001; Paragamian and others, 2001). Stage-discharge relations simulated by the model are described by relating three parameters—discharge, water-surface elevation (stage plus datum, see glossary), and location of transition between backwater and free-flowing water in the study reach. The study reach (figs. 1 and 2) is the Kootenai River from Leonia downstream to Porthill, Idaho, with the primary focus in the white sturgeon spawning reach near Bonners Ferry (fig. 2B).



A. River miles 156 to 172

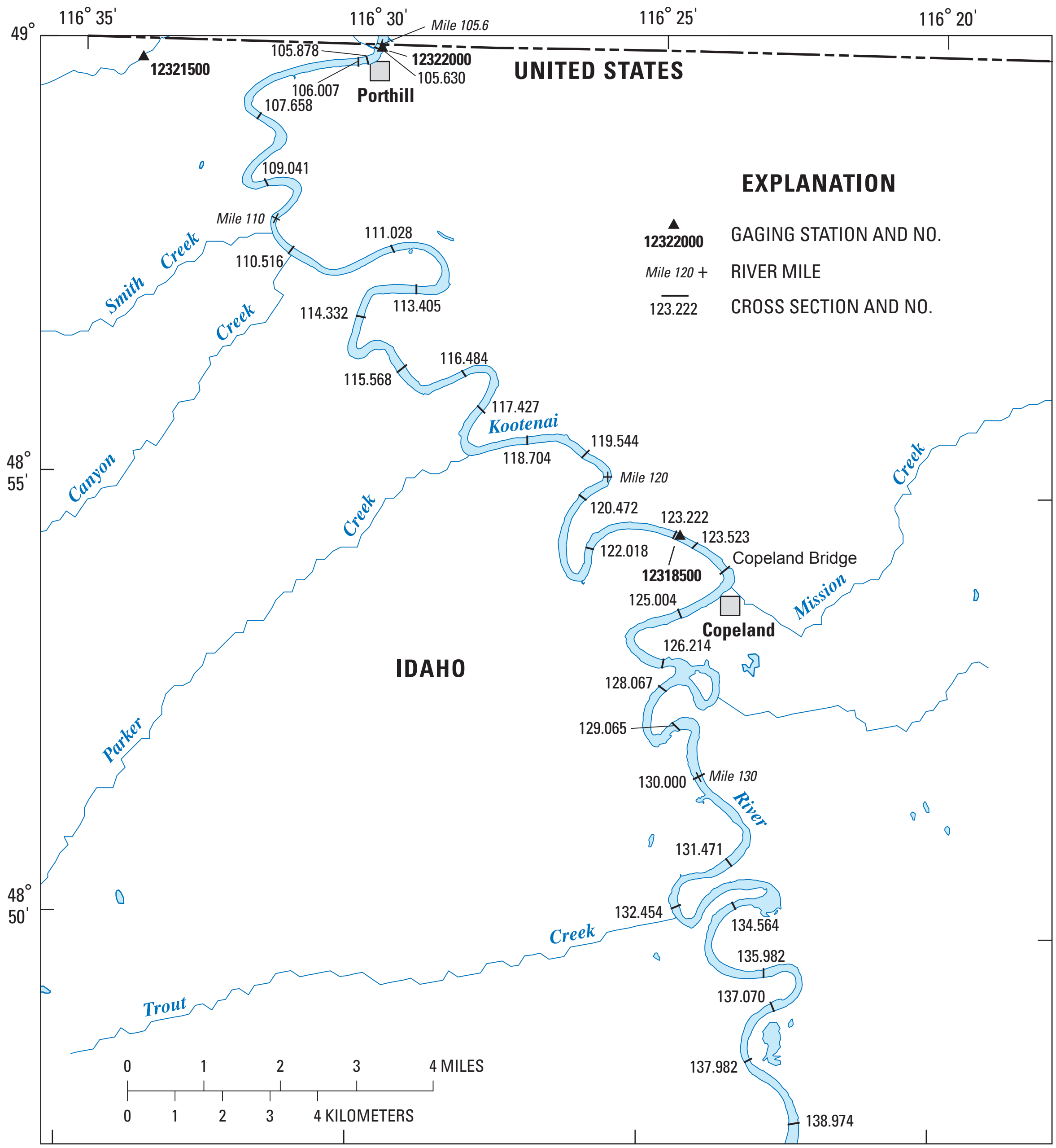
Figure 2. Locations of stream channel cross sections and river miles on the Kootenai River, Idaho.

The scope of this report includes (1) definition of channel geometry, flow types, and river stages in the study reach; (2) development and calibration of a one-dimensional hydraulic-flow model of the study reach using the U.S. Army Corps of Engineers HEC-RAS model (Brunner, 2002a, 2002b); and (3) use of the one-dimensional model to determine the location of transition between backwater and free-flowing water in the white sturgeon spawning reach. Modeling included the simulation of a range of river stages at the Kootenai River at the Porthill gaging station (12322000) and discharge in the study reach. Simulated water-surface elevation at Porthill ranged from 1,741 to 1,762 ft, and simulated discharge in the study reach ranged from 4,000 to 75,000 ft^3/s.



B. River miles 139 to 156

Figure 2.—Continued



C. River miles 105.5 to 139

Figure 2.—Continued

Description of Study Reach

The Kootenai River originates in the Rocky Mountains in British Columbia, Canada, and flows southward into man-made Lake Koocanusa in British Columbia and Montana (fig. 1). The river below Libby Dam flows westward through Montana and part of Idaho until it is joined by Deep Creek near Bonners Ferry, Idaho. The river then flows north from Deep Creek to Kootenay Lake in British Columbia (figs. 1 and 2). The river flows westward from the outlet on the west side of Kootenay Lake and joins the Columbia River near Castlegar, Canada. The Kootenai River is referred to as the Kootenay River in British Columbia. For the purpose of this report and as a matter of convenience, the United States spelling "Kootenai" will be used when referring to the river and the Canadian spelling "Kootenay" will be used when referring to the lake because the lake is located entirely within British Columbia, Canada.

The Kootenai River is 448 mi long and drains an area of 17,600 mi^2. The elevation of the river at its headwaters in British Columbia is about 11,900 ft, and at the confluence with Kootenay Lake, the elevation is about 1,745 ft. River length from Libby Dam, the outlet of Lake Koocanusa, to Kootenay Lake is about 145 mi.

The study reach of the Kootenai River is a 65.6-mi reach starting at Leonia, Idaho (RM 172; fig. 2*A*), and ending at the International Border near Porthill, Idaho (RM 105.6) (fig. 2*C*). This reach encompasses the white sturgeon spawning reach (RM 139.8 to RM 153.3), and includes an approximately 1-mi-long channel around the western side of Shorty Island. The side channel is much shallower and narrower than the main river channel on the eastern side of the island. Much of the study reach is in backwater because water in Kootenay Lake backs upstream into the Kootenai River to the reach near Bonners Ferry. Backwater conditions occur continuously at the confluence of Deep Creek and the Kootenai River (RM 149.2) (Barton, 2003). In spring and early summer (periods of high flow), free-flowing water may extend several miles downstream of the U.S. Highway 95 Bridge (RM 152.8). The transition between backwater and free-flowing water migrates upstream or downstream near Bonners Ferry in response to changes in discharge in the river and changes in Kootenay Lake elevations. Backwater conditions usually extend 1 to 2 mi upstream of Bonners Ferry. The extent of backwater has been up to the vicinity of Crossport, about 4 mi upstream of Bonners Ferry (figs. 1 and 2). The levels in Kootenay Lake generally are at a minimum in autumn and winter and maximum in late spring and early summer because of snowmelt runoff.

Three geomorphic reaches were identified in the study reach—a canyon reach, a braided reach, and a meander reach (Synder and Minshall, 1996). The canyon reach extends from Libby Dam (RM 220) to Crossport (RM 159.5) (figs. 1 and 2) where the valley begins to widen. The braided reach extends from RM 159.5 to a bedrock constriction near the U.S. Highway 95 Bridge (RM 152.8) at Bonners Ferry. The meander reach extends downstream of the bedrock constriction at Bonners Ferry to Kootenay Lake (about RM 77).

The canyon reach consists of a long, straight single channel with steep canyon walls and is incised into bedrock. Water depths are usually 20 ft, and water-surface slope is about 3×10^{-4} ft/ft. White sturgeon spawning has not been detected in the canyon reach.

The braided reach usually consists of multiple channels, and the streambed is composed primarily of gravels and cobbles. Water depths usually are less than 7 ft, and water-surface slope is about 4.6×10^{-4} ft/ft. White sturgeon spawning has not been detected in the braided reach (Paragamian and others, 2002).

The meander reach is a single channel with gentle bends. From U.S. Highway 95 Bridge to Ambush Rock (RM 151.9) (fig. 2*B*), the streambed consists primarily of gravel and cobbles with some sand; and downstream of Ambush Rock, the streambed consists primarily of sand. Water depths in the meander reach usually exceed 40 ft, and the water-surface slope is about 2×10^{-5} ft/ft, less than one-twentieth or 20 times less than the slope in the braided reach. Sand dunes occur throughout the meander reach including reaches used by the sturgeon for spawning (Barton, 2004). Sturgeon mostly spawn in the meander reach between RM 141.6 and RM 149.0 (Paragamian and others, 2001 and 2002; Paragamian and Kruse, 2001). In 2001, sturgeon spawned below the U.S. Highway 95 bridge.

The model was calibrated using stage or flow information from five USGS gaging stations located in the study reach (fig. 2). Four gaging stations, Kootenai River at Leonia (12305000), Kootenai River at Bonners Ferry (12309500), Kootenai River at Klockmann Ranch near Bonners Ferry (12314000), and Kootenai River at Porthill (12322000) have been in operation since the late 1920s. Two of the gaging stations (Bonners Ferry and Klockmann Ranch) only have stage data because of backwater conditions at the sites. Discharge is not a function of stage alone in backwater conditions. The Porthill gaging station also is in backwater, but discharge has been calculated using two approaches. Discharge at the Porthill gaging station has been estimated using a one-dimensional hydraulic-flow model (Schaffranek and others, 1981) based on water-surface elevation data for Porthill and Klockmann Ranch gaging stations and discharge data for Boundary Creek near Porthill (12321500; fig. 2*C*). An acoustic Doppler velocity meter (ADVM) was installed at the Porthill gaging station in October 2001. Discharge since January 2004 has been determined using relations between stage and flow area and between velocity from the ADVM and average velocity at the gaging station. In September 2002, a new gaging station was installed at the Kootenai River at Tribal Hatchery near Bonners Ferry (12310100) using an ADVM. Discharge at the Tribal Hatchery gaging station also is calculated by a velocity-stage-discharge relation using the ADVM data. A more complete discussion on the computation of discharge at sites using ADVMs is provided in Morlock and others (2002). The Leonia gaging station is the only station in the study area for which discharge is calculated by a stage-discharge relation.

From mid/late summer through early/mid spring, flow in the river primarily is regulated by Libby Dam, Montana, which is about 70 mi upstream of Bonners Ferry, Idaho (fig. 1). From mid/late spring through early/mid summer, the major contribution of flow to the river is from melting snow from tributary areas below Libby Dam.

Previous Investigations

The first model of the Kootenai River was developed by the USGS in 1980 for explicitly determining the amount of streamflow entering British Columbia, Canada, from Idaho for the International Joint Commission (Schaffranek and others, 1981, p. 45-49). In backwater reaches such as those in this study, discharge is not a function of stage alone, and stage-discharge relations do not work. There may be many stages for one discharge or many discharges for one stage. To determine discharge entering British Columbia, Canada, a BRANCH model (1D unsteady flow) was developed from stage data at the Klockmann (12314000) and Porthill gaging stations (12322000) (Schaffranek and others, 1981). The model used seven cross sections and had the ability to include inflows from tributaries. The model was used to calculate flow at Porthill until January 2004.

A flood insurance study completed in 1985 modeled only the river adjacent to Bonners Ferry (Federal Emergency Management Agency, 1985). The model is comprised of five cross sections for a total reach length of 5,800 ft. Cross-sectional data for the river banks and floodplain were based on aerial surveys. The bathymetry was field surveyed in 1983. Manning's roughness coefficients of 0.035 were used for the main channel and 0.060 for the river banks and floodplain.

A one-dimensional unsteady flow model, UNET, was developed by the U.S. Army Corps of Engineers (COE) in 1995 (Patrick McGrane, written commun., 1995). This model extends from Bonners Ferry to Queens Bay, British Columbia, Canada, and comprises 54 cross sections. Cross sections in Idaho were surveyed in 1982, and sections in Canada were surveyed in the 1990s. The model was calibrated to high-water marks collected in 1974 and to lake elevations in Kootenay Lake. The COE developed three-parameter relations between Kootenay Lake elevation, discharge at Bonners Ferry, and cross-section velocity. A plot of the relation of three parameters (average velocity, water-surface elevation at Queens Bay gaging station [08NH064], and discharge at Bonners Ferry [12309500]) was developed for every cross section in Idaho.

In 2003, a HEC-RAS model contained within the white sturgeon spawning reach was developed by Tetra Tech, Inc., and Perkins Geosciences (2004) for COE. The model used preliminary cross sections surveyed in 2002 by the USGS (Barton and others, 2004). About 50 cross sections were used and were adjusted to National Geodetic Vertical Datum of 1929 (NGVD 29) from North American Vertical Datum of 1988 (NAVD 88) by subtracting 3.64 ft (approximate conversion, Tetra Tech, Inc., and Perkins Geosciences, 2004, p. 48). They also chose a Manning's n of 0.035 for the channel portion and 0.060 for the river bank portions of the cross section because these values were used in the 1985 flood insurance study. This model was not calibrated (Tetra Tech, Inc., and Perkins Geosciences, 2004). Model results were used to determine hydraulic conditions and bed-sediment motions.

Reach Characteristics

An understanding of flow and hydraulic geometry of the Kootenai River is necessary before a hydraulic model of the river can be developed. This involves understanding the reach characteristics, such as channel geometry, flow, and stage.

Channel Geometry

Channel geometry (cross sections and longitudinal sections) data of the Kootenai River were collected during 2002–03 in support of modeling needs. Cross sections (fig. 2) from the river survey by Barton and others (2004) were used to define channel geometry for the hydraulic-flow model. Cross sections used in this study are located between the Leonia gaging station (12305000) (RM 171.875) and the Porthill gaging station (12322000) (RM 105.603).

A complete description on the surveying, quality control, and processing of these cross sections are given in Barton and others (2004). The cross-section data are accessible at URL http://id.water.usgs.gov/projects/kootxsections/cross.htm. A geo-referenced shapefile of these cross sections also is available at the above web address. Horizontal control was based on North American Datum of 1983 (NAD 83), Idaho Transverse Mercator Coordinates, in meters; vertical control was based on NAVD 88, in feet.

Channel cross sections differ between the canyon, braided, and meandering reaches. Cross sections in the canyon reach have widths ranging from 400 to 500 ft, and depths usually are less than 20 ft. The channel in this reach tends to be long and straight. In the braided reach, cross sections are about twice as wide as sections in the canyon reach with shallower depths (7 ft). These cross sections at low flows have exposed islands and (or) bars that divide the river into separate channels. At higher flows, the islands and (or) bars are likely submerged. However, there are a few permanent islands in this reach near RM 154. Cross sections in the meandering reach are about 600 ft wide with depths greater than 25 ft through depths greater than 50 ft. Cross sections for each of these reaches are given in Barton and others (2004, p. 12-14).

Eight cross sections on the side channel of Shorty Island were generated by using Triangulated Irregular Network (TIN) data obtained from many longitudinal surveys and several cross section surveys of the reach. The side channel was usually too narrow and shallow to obtain adequate cross sections using a boat equipped with an echo sounder and global positioning system (GPS) equipment (Moran and Berenbrock, 2003). Therefore, many longitudinal surveys were made in the side channel (Rick Backsen, U.S. Geological Survey, oral commun., 2003). These cross sections usually are less than 100 ft wide and usually less than 10 ft deep.

Flow Types

The Kootenai River in the study reach, especially in the white sturgeon spawning reach, is affected by the elevation of Kootenay Lake. The Corra Lynn Dam at the outlet of Kootenay Lake causes water to back up (increase in water-surface elevation) into the Kootenai River. Before construction of the dam, a natural barrier at Grohman Narrows and Bonnington Falls (fig. 1) confined and dammed the water behind it into the lake and upstream into the river.

The spawning reach is usually in backwater and the upper parts of the study reach are sometimes in free-flowing conditions. Backwater conditions are prevalent in the river below the mouth of Deep Creek (RM 149.2). Hypothetical water-surface curves have been developed to illustrate backwater and free-flowing conditions. Figure 3 represents these two flow types. The backwater curve is commonly called an M_1 curve by hydraulic engineers, and the free-flowing water curve (above critical depth) is called an M_2 curve. These curves and others are described by Woodward and Posey (1941), Chow (1959), and Henderson (1966). If the illustrative reach in figure 3 were elongated upstream, the backwater and free-flowing water curves would converge to the normal-depth curve. At the point where the backwater curve (M_1) approaches or converges to the normal-depth curve, the effects of backwater cease. The normal-depth curve also is known as the no-backwater curve (Davidian, 1984, p. 3). Any water-surface curve at or below the normal-depth curve is not affected by backwater conditions. Figure 3 also illustrates that high downstream water-surface elevations cause the convergence point with the normal-depth curve to be farther upstream. The influence of backwater conditions on the reach is moved upstream and has a longer extent with higher downstream water-surface elevations.

In natural channels like the Kootenai River, the curves are not as smooth as shown in figure 3, because flow depth changes from point to point along a channel in response to differences in channel shape, slope, and roughness. Figure 4 shows backwater, normal depth, and free-flowing water curves for the Kootenai River in the study reach for a model simulation of 30,000 ft^3/s at six water-surface elevations at Porthill gaging station (12322000) (RM 105.603). Two of the curves are below the normal-depth curve indicating that the reach has free-flowing water for the specified discharge and downstream water-surface elevations, and four curves are above the normal-depth curve (backwater conditions). Figure 4*B* shows the four backwater curves transitioning from backwater conditions to free-flowing conditions between RM 153 and 157. For example, the curve at a water elevation of 1,760 ft (fig. 4*B*) transitions from backwater to free-flowing conditions at RM 156.3.

River Stage

For this study, water-surface elevation at a gaging station was calculated by adding the river stage value to the NAVD 88 datum at the gaging station. River stages (or water-surface elevations) have been measured on Kootenay River and Kootenai Lake for almost a century. Cross sections were surveyed during 2002–03 (Barton and others, 2004) and stage datums at gaging stations were surveyed using GPS so that all data can be converted to one common datum. For this study, NAVD 88 was used. Datum elevations in NVGD 29 and NAVD 88 at gaging stations in Montana, Idaho, and British Columbia, Canada, on the river and lake are shown in table 1. Differences between NAVD 88 and NVGD 29 are not the same everywhere (table 1) because of the Earth's irregular curvature.

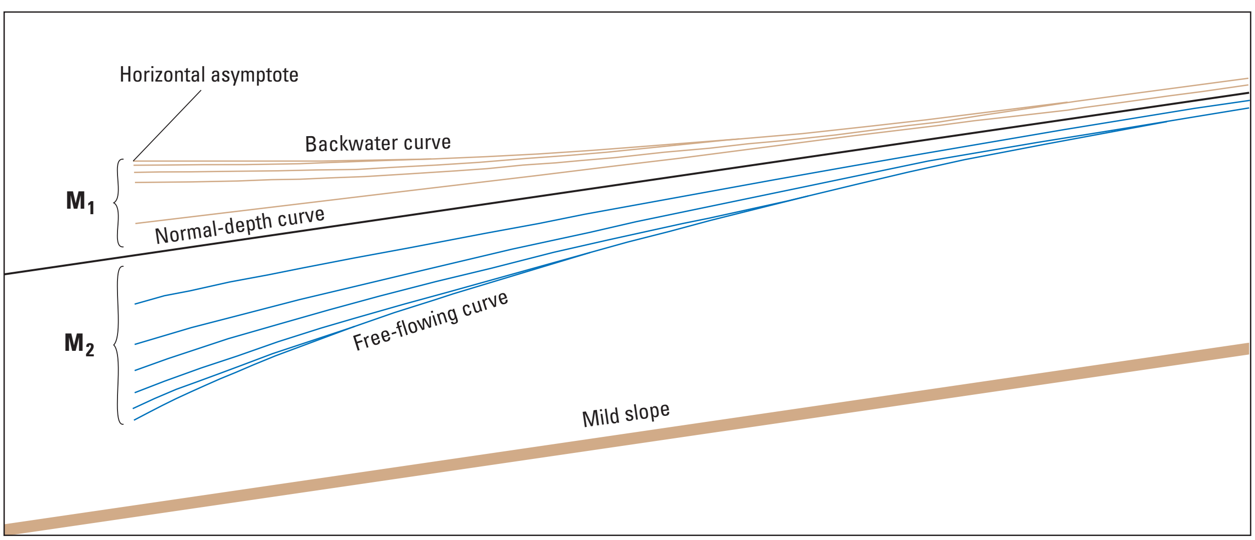


Figure 3. Water-surface curves along a constant, uniform, mild-sloped channel. (Modified from Davidian, 1984, fig. 10, p. 8).

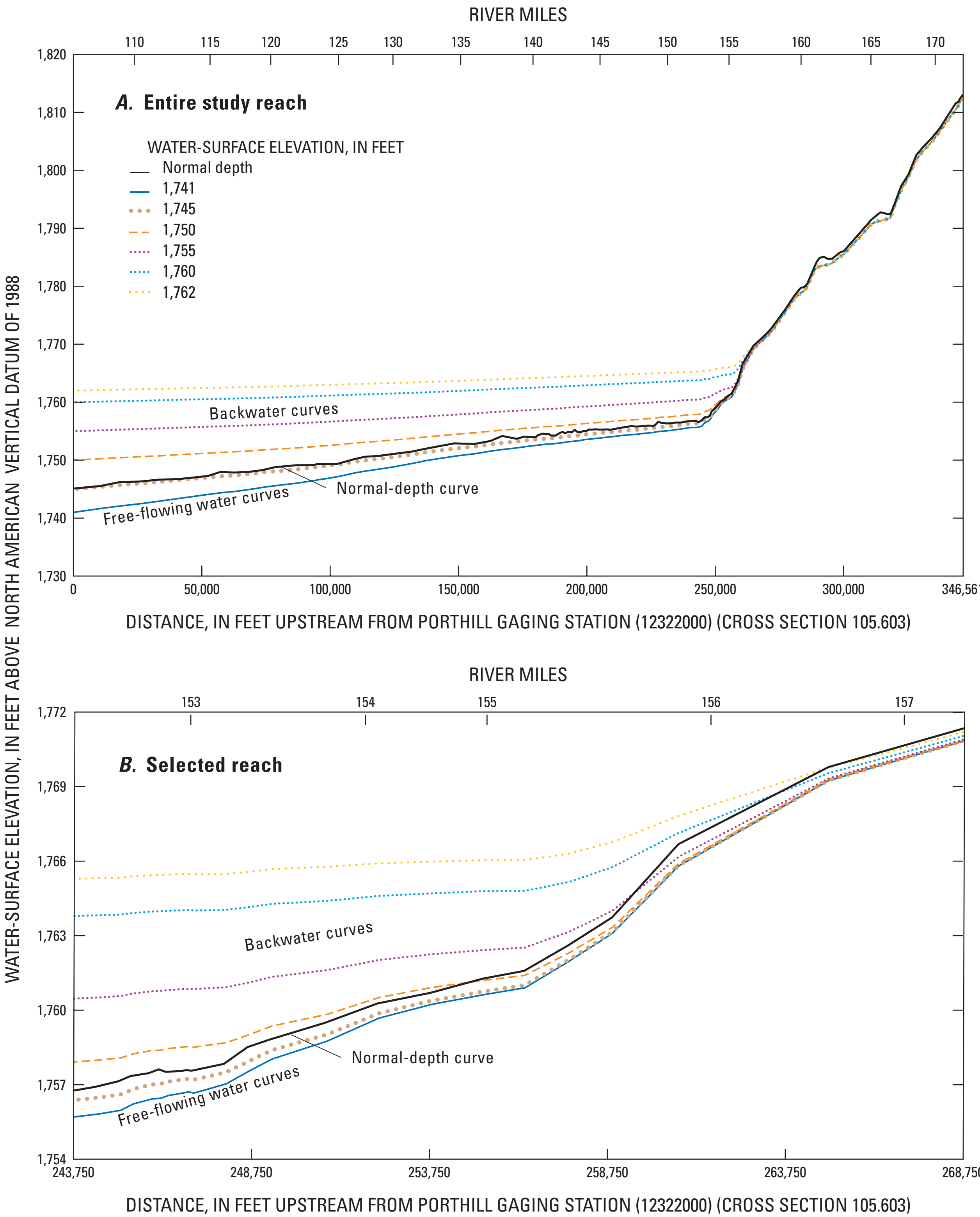


Figure 4. Simulated water-surface curves for a discharge of 30,000 cubic feet per second in the entire study reach and in a selected reach, Kootenai River, Idaho.

Table 1. Elevation of river stage datums at U.S. Geological Survey and Canadian gaging stations on the Kootenai River and Kootenay Lake, Montana, Idaho, and British Columbia, Canada.

[Locations of gaging stations are shown in figures 1 and 2. **Datum elevation**: NGVD 29, National Geodetic Vertical Datum of 1929; NAVD 88, North American Vertical Datum of 1988. **Datum difference:** NAVD 88 minus NGVD 29. ft, foot; –, no data]

Gaging station No.	River mile	Site Name	Datum elevation (ft)		Datum difference (ft)
			NGVD 29	NAVD 88	
12301933	221.238	Libby Dam	2,100.000	2,103.748	3.748
12305000	171.875	Leonia	1,790.250	1,793.690	3.440
12309500	152.790	Bonners Ferry	1,700.000	1,703.820	3.820
12310100	149.910	Tribal Hatchery	–	1,699.880	–
12314000	139.469	Klockmann Ranch	1,700.000	1,703.800	3.800
12322000	105.603	Porthill	1,700.000	1,703.896	3.896
[1]08NH067 or 12322500	[2]74.5	Kuskonook	1,700.000	1,704.052	4.052
[1]08NH064	47.273	Queens Bay	1,700.000	1,704.012	4.012

[1] Canadian gaging station identifier.
[2] O'Dell and others (2002).

The stage of Kootenay Lake has been measured since the 1920s (Barton, 2004) at several gaging stations and reflect changes made at the lake's outlet and changes in inflow because of Libby Dam. At Queens Bay, stage has been measured since the early 1930s (fig. 5). Water-surface elevations at Queens Bay show seasonal fluctuations—maximum during spring and early summer months by snowmelt runoff and minimum during autumn and winter months (fig. 6). In 1939, the river channel above Corra Lynn Dam at Grohman Narrows was deepened and obstructions in the channel were removed to increase flow in the river and reduce hydraulic losses in the forebay of the dam (International Joint Commission, 1938, Order of Approval, Kootenay Lake (http://www.ijc.org/conseil_board/kootenay_lake/en/kootenay_mandate_mandat.htm). This also allows the lake to be kept at a lower elevation for dam operation, and thus, reduces the backwater effect in the Kootenai River. After the deepening of Grohman Narrows and prior to the completion of Libby Dam (1940 to 1972), lake elevations ranged from 1,766.0 to 1,741.5 ft and averaged 1,749.3 ft (fig. 5). During the Libby Dam era from 1973 to 2003, lake elevations ranged from 1,758.3 to 1,742.1 ft and averaged 1,747.7 ft (fig. 5). The most notable difference between these two periods is the reduction or the absence of the spring and early summer peaks during the Libby Dam era; the maximum peak was reduced 7.7 ft. The average lake elevation has been lowered 1.6 ft during the Libby Dam era (fig. 5).

Water-surface elevations for gaging stations on Kootenay Lake and Kootenai River through the backwater reach have similar patterns (fig. 6) but are at different elevations, reflecting the variable water-surface elevations of the backwater curve (M_1) through the reach. For example, when elevations in the lake (Queens Bay on Kootenay Lake) increase, water-surface elevations also increase in the river (Porthill, Klockmann Ranch, and Bonners Ferry gaging stations).

Stage-stage relations between Queens Bay and each of the three river gaging stations (Porthill, Klockmann Ranch, and Bonners Ferry) were developed (fig. 7). These curves relate the stage in the lake to stage in the river reasonably well. The curves and equations were derived using simple linear regression methods. These equations relate the water-surface elevation at Queens Bay to water-surface elevations at the respective gaging stations. The *r* value (correlation coefficient), *k* value (number of paired data points), and the period of record for the paired data are shown in figure 7. The correlation coefficient is a measure of strength of the linear relation between two variables (Zar, 1998). An *r* value of 0 indicates that there is no linear association between the two variables, whereas, an *r* value of 1 or –1 indicates a strong linear association. The correlation coefficient of water-surface elevations for the Queens Bay and Porthill gaging stations was 0.95 (strong correlation). The correlation of water-surface elevation for the Queens Bay gaging station with the other Kootenai River gaging stations (Klockmann Ranch and Bonners Ferry) was weaker ($r = 0.83$ and $r = 0.77$, respectively). The *r* value decreased as distance increased from Kootenay Lake, probably because of the influence of inflows from intervening drainages and (or) the effects of backwater in the river.

The simple linear regression curves in figures 7*A*, 7*B*, and 7*C* fit the data acceptably when water-surface elevations are below 1,752.5 ft at Queens Bay, but they should not be used when water-surface elevation is above 1,752.5 ft at Queens Bay. Above 1,752.5 ft, the data trend in another direction from the regression curve. Improvements to these relations can be made by using several linear regressions or non-linear function(s) that describes the entire dataset more accurately.

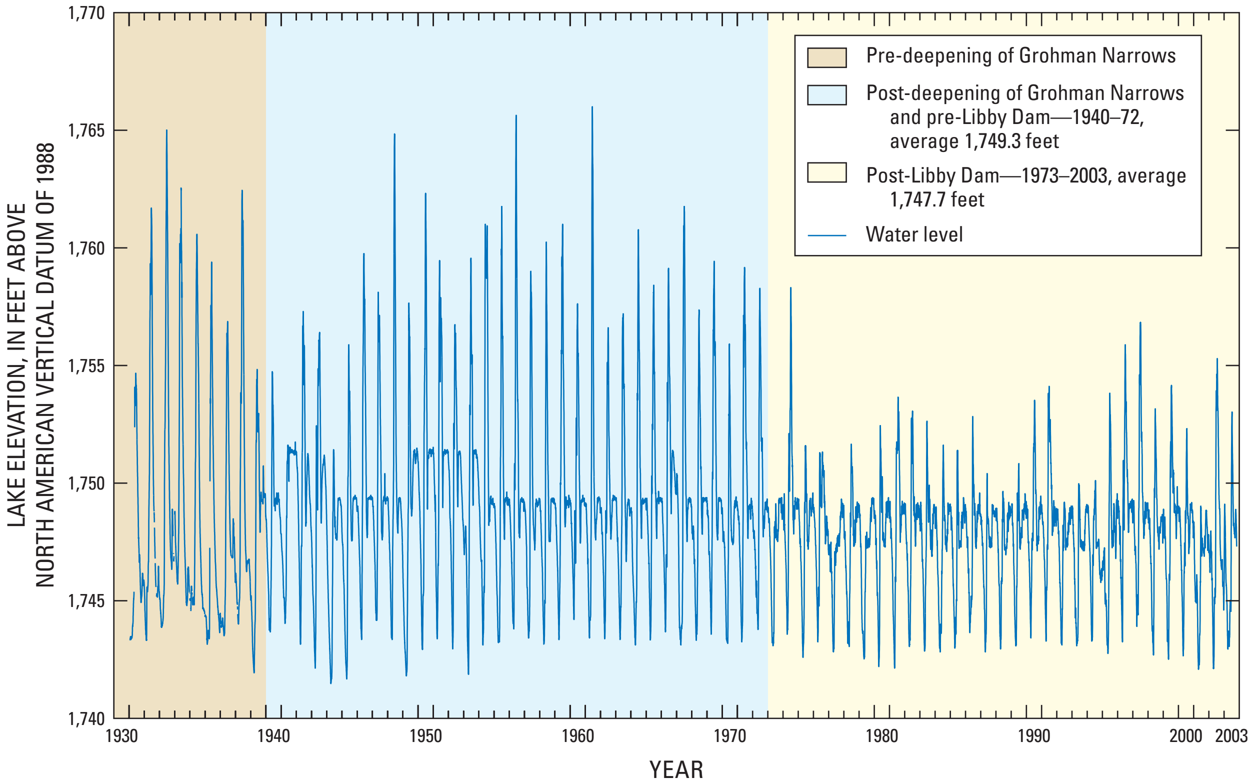


Figure 5. Daily water levels on Kootenay Lake at Queens Bay (08NH064), British Columbia, Canada. (Data from Environment Canada). (Location of gaging station is shown in figure 1.)

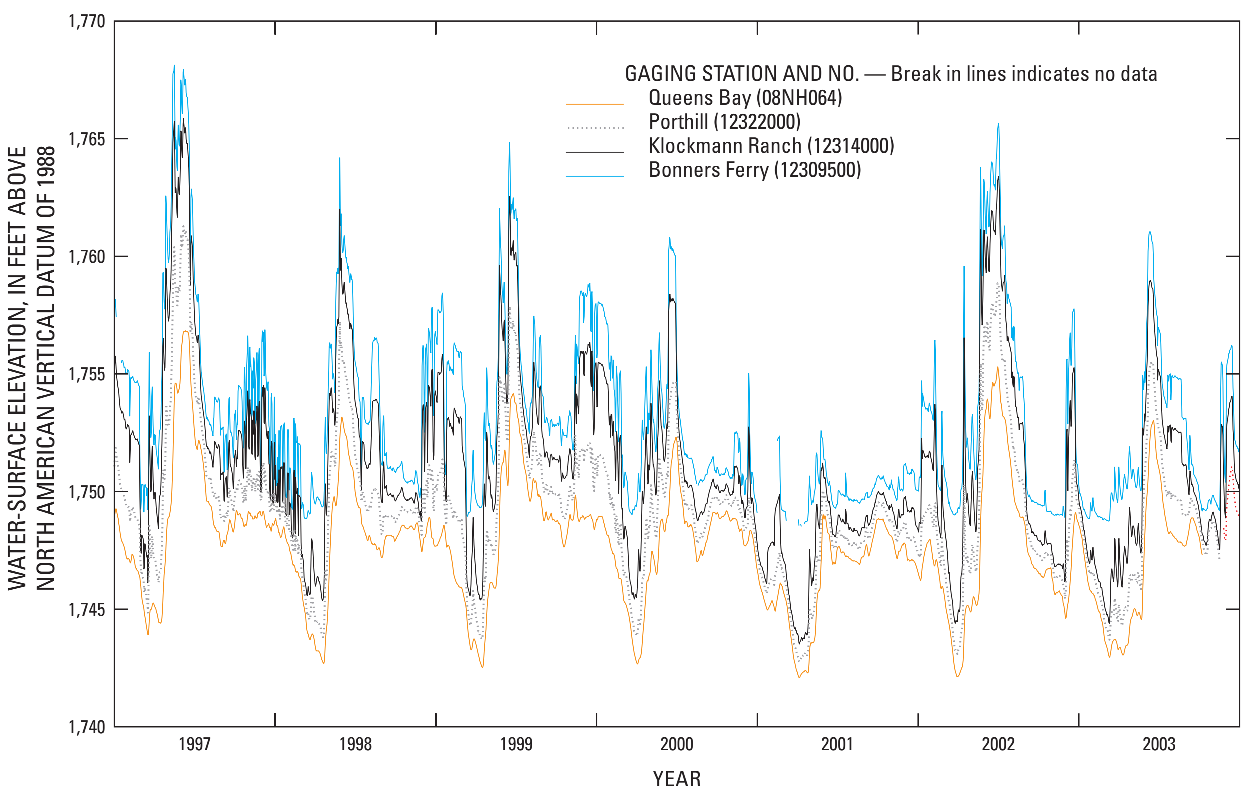


Figure 6. Water-surface elevations at selected gaging stations on the Kootenai River and Kootenay Lake, 1997–2003. (Locations of gaging stations are shown in figures 1 and 2.)

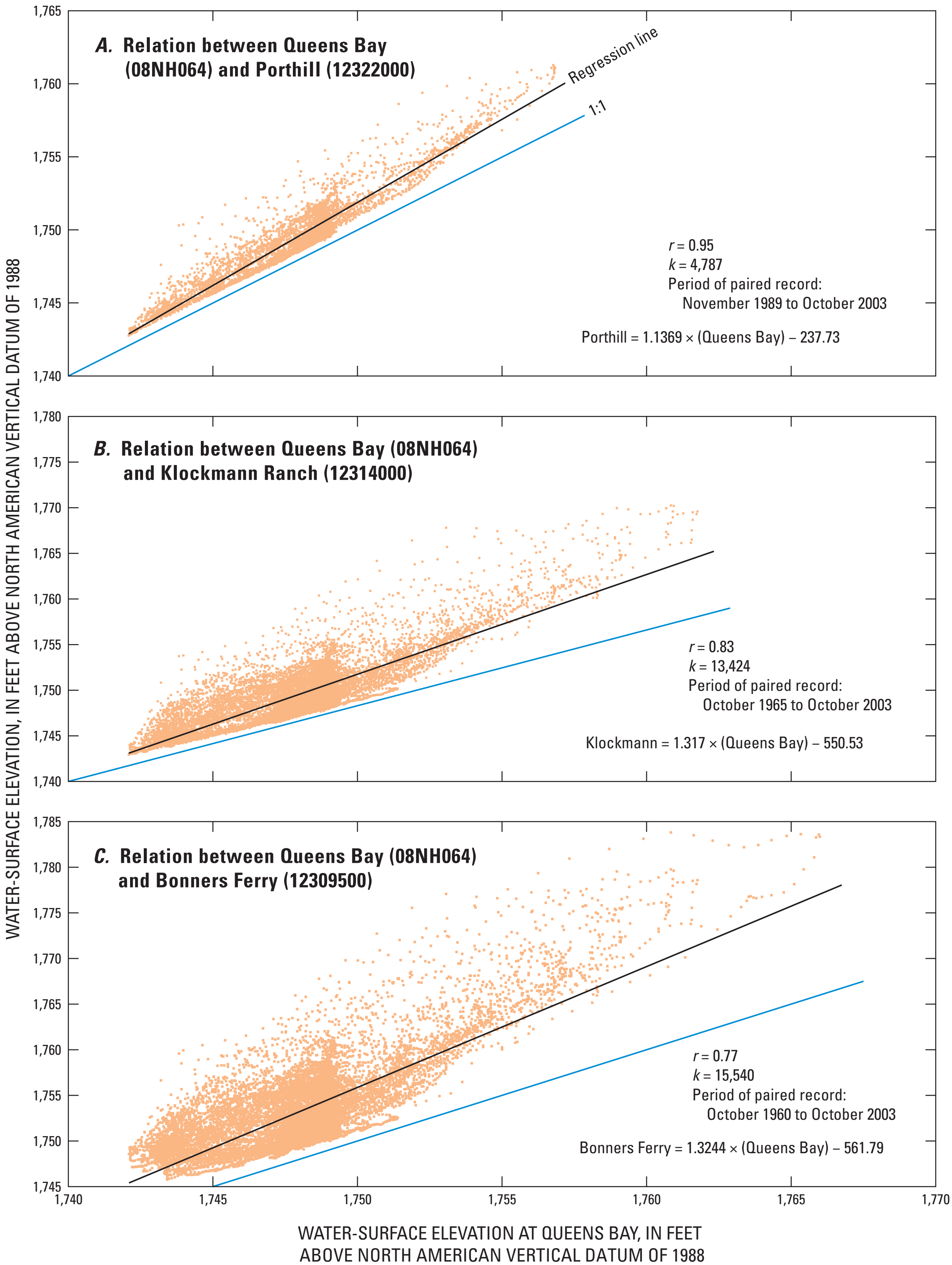


Figure 7. Relation between water-surface elevation for Queens Bay on Kootenay Lake and selected gaging stations on the Kootenai River in the study reach, Idaho.

Model Development and Calibration

The HEC-RAS computer model, version 3.1 (Brunner, 2002a and 2002b; and Warner and others, 2002) was used to construct a surface-water, hydraulic-flow model of the Kootenai River to determine the location of transition between backwater and free-flowing water in the study reach. In previous modeling studies of this reach and for this present study, the streambed was assumed to remain stable during all flows, and sediment-transport processes were not simulated. The modeled reach extended from the Leonia to the Porthill gaging stations—an actual distance of 65.6 mi.

A difference of 1.4 mi exists between the distance calculated using the river-mile (RM) designators (67 mi) and the actual distance (65.6 mi) used in the model. The distance of 67 mi was based on river mile differences. River miles generally are measured in 1-mi increments along the channel centerline in an upstream direction beginning with 0 at the river mouth, which, in this case, was the outlet to Kootenay Lake. River-mile designations were derived by the Columbia Basin Inter-Agency Committee (1965) and usually are shown on USGS 7.5-minute (1:24,000-scale) maps. Since the publication of these documents, the channel length in several places along the Kootenai River has changed somewhat because of bank erosion, deposition, or channel migration. As a result, the actual distances between the river-mile designators shown on the maps are not always exactly 1.0 mi. However, these designators are used because many people are familiar with them and use them for various purposes. However, actual distances between cross sections were used in the model.

HEC-RAS is a computer program that simulates one-dimensional, gradually varied, steady flow in open channels with fixed boundaries. The model uses the standard step method (Chow, 1959, p. 265) to determine changes in water-surface elevations from one cross section to the next by balancing total energy head at the sections. This one-dimensional model assumes that energy is uniform in a cross section. This assumption is not accurate in locations where flow is not parallel to the main channel or where vertical velocities are significant. The model also assumes that flow is unobstructed, thus, the channel and floodplain contain no debris.

Model Cross Sections

A total of 164 cross sections were used in the model: 131-field-surveyed, 8 Triangulated Irregular Network (TIN) generated, 2 bridges, and 23 interpolated. The field-surveyed cross sections by Barton and others (2004) were used to define channel geometry characteristics for the initial HEC-RAS model. Eight TIN-generated cross sections were developed for the Shorty Island side channel, and two bridge cross sections were generated from bridge design plans.

Though the HEC-RAS model is capable of simulating flow through bridges and (or) culverts, two bridges were not incorporated into the model. The ratio of bridge-pier area to flow area for the Highway 95 Bridge was less than 5 percent; thus, the piers probably do not significantly constrict the flow through the bridge. The lowest part of the bridge deck is higher than the 500-year flood elevations (Federal Emergency Management Agency, 1985) indicating no pressure flow will occur through the bridge. These factors were similar for the railroad bridge that is about 0.5 mi downstream of the Highway 95 Bridge (fig. 2*B*).

However, the Copeland Bridge was included in the model because parts of the bridge are below the elevation of the river banks or levees, and the bridge might cause pressurized flow at high stages and (or) discharges. Two cross sections were generated from bridge design plans of the Copeland Bridge (Lotwick Reese, Idaho Transportation Department, written commun., 2004). Because only one cross-section profile was given on design plans and considering the narrow width of the bridge, the two cross sections were made identical and were located immediately upstream and downstream of the bridge in the model.

Twenty-three interpolated cross sections were generated at various locations along the reach by interpolating data from two adjacent surveyed cross sections to minimize flow conveyance changes between the surveyed cross sections, thereby maintaining computational stability. For example, cross section 152.510 was interpolated from upstream cross section 152.628 and downstream cross section 152.392. Interpolation was computed by averaging data from the two cross sections because cross section 152.510 was centered between the upstream and downstream cross sections. This interpolation was done using a feature of the HEC-RAS model. Interpolated cross sections improve the convergence of the solution and the solution of the water surface.

Actual flow distances between cross sections were used in the model, not the distance from subtracting cross section river-mile designators to compute friction losses. For example, the actual flow distance between cross sections 144.618 and 144.979 is 1,436.5 ft. Based on the river-mile designators, the distance is 1,906.1 ft (144.979 mi – 144.618 mi = 0.361 mi × 5,280 ft/mi = 1,906.1 ft). The resulting difference between the two is 469.6 ft (1,906.1 ft – 1,436.5 ft = 469.6 ft). The average difference in the study reach between actual flow and river-mile designator distances is about 270 ft. Using actual flow distances gives a better estimate of friction losses than using the more arbitrary river-mile designator distances.

The model requires a roughness coefficient (Manning's *n*) at every cross section to represent the flow resistance in the channel. Factors that affect flow resistance include: (1) size, gradation, and angularity of particles comprising the streambed; (2) channel shape; (3) type of bed forms (dunes, antidunes, and ripples and the presence of bars); (4) riparian vegetation; (5) man-made and natural structures (levees and bridges); (6) presence of suspended sediment and movement of the streambed; and (7) degree of meandering. Resistance usually decreases as flow increases because the streambed exerts less of an effect on flow as depth increases. Resistance also decreases as the size of the bed material decreases. Generally, for alluvial channels with coarse materials, streambed particle size and gradation probably are more important than other factors for determining flow resistance.

Roughness coefficients established from the previous model of the river and floodplain (Federal Emergency Management Agency, 1985) were used as the starting values for this study. The Federal Emergency Management Agency (FEMA) model that was developed for the Bonners Ferry Flood Insurance Study assigned a Manning's *n* value of 0.035 to the streambed and 0.060 to the river banks. These values were later adjusted during model calibration. Differences in *n* values between the streambed and river banks are attributed to differences in surface roughness (size and shape of grains); vegetation (density, distribution, and type); geometry (size and shape); and obstructions (woody debris, vegetation, vehicle bodies, riprap). For example, river banks downstream of Crossport generally are quite dense with low to high brush and trees although upstream, the river banks are composed primarily of large boulders with few trees and brush. Near the Kootenai National Wildlife Refuge, large boulders (riprap) line the river banks.

Model Boundaries

Because subcritical flow is the dominant flow condition in the study reach, the model requires discharge data at the upstream boundary (cross section 171.875), and water-surface elevation at the downstream boundary (cross section 105.603). Discharge at the upstream boundary (cross section 171.875) was based on discharge data from the Leonia gaging station (12305000). Discharges from the Moyie River were calculated by subtracting flow at the Tribal Hatchery gaging station (12310100) from the Leonia gaging station because flows from the Moyie River are not gaged near the confluence with the Kootenai River. Water-surface elevation at the downstream boundary (cross section 105.603) was based on adding stage data from the Porthill gaging station (12322000) and the NAVD 88 datum.

Model Calibration

Calibration is the process of adjusting model parameters within reasonable limits to obtain the best fit of model results to measured data. The process is to repeatedly adjust a parameter, run the model, and inspect the difference between model results and measured data with the objective of minimizing the difference. In this study, calibration consisted of comparing the difference between simulated and measured water-surface elevations at selected sites and adjusting the initial roughness coefficients to minimize the difference. In the model, *n* values were used as a calibration parameter and were adjusted between minimum and maximum values for the type of channel and flow (Chow, 1959, table 5-6). Model calibration was considered acceptable when the difference between measured and simulated water-surface elevations for each calibration point was within the limit of ±0.15 ft.

Calibration at first consisted of comparing simulated and measured steady-state water-surface elevations at the Klockmann Ranch gaging station (12314000; fig. 2*B*), Tribal Hatchery gaging station (12310100; fig. 2*B*), Bonners Ferry gaging station (12309500; fig. 2*B*), and the Leonia gaging station (12305000; fig. 2*A*). Nine calibration points in 2002 and 2003 were identified where discharge and water-surface elevation remained steady through the study reach for at least several days. Discharge was based on a daily mean discharge from the Tribal Hatchery gaging station. Because the Tribal Hatchery gaging station was not in operation prior to water year 2003, the 47,500 ft^3/s discharge was calculated by subtracting discharge at the Boundary Creek gaging station (12321500, fig. 2*C*) from the Porthill gaging station (12322000; fig. 2*C*) for the previous day, to account for time of travel. Water-surface elevation was based on a daily mean stage at the Klockmann Ranch, Tribal Hatchery, and Bonners Ferry gaging stations. Water-surface elevations for the Leonia gaging station were based on the stage-discharge rating curve. Water-surface elevation at a gaging station is derived by adding stage to the gaging stations NAVD 88 datum.

Historical stage and discharge data prior to 2002 were not used in the calibration of this model because the current cross-section geometry might not be representative of historical conditions. In a comparison of historic (1920 and 1956) cross sections to 2002-03 cross sections (Barton and others, 2004) in the white surgeon spawning reach, Tetra Tech, Inc., and Perkins Geosciences (2004) indicated that the average streambed change ranged from 1 to 2 ft at most cross sections. Changes greater than 3 ft occurred at several cross sections and about 5 ft at one cross section. Overall, they indicated that a significant amount of deposition occurred in the study reach between historic (1920 and 1956) and 2002. At the Copeland gaging station (12318500) (RM 123.222), the average streambed change of about 5 ft also occurred between 1931 and 1972 and about 2.5 ft between 1973 and 1993 (Barton, 2004, fig. 16).

Table 2. Measured and simulated water-surface elevations, Kootenai River, Idaho.

[Locations of gaging stations and cross sections are shown in figure 2. Water-surface elevations for the Leonia gaging station are based on the stage-discharge rating curve. CS, cross section; ft, foot; ft^3/s, cubic foot per second; –, no data]

Daily mean discharge (ft^3/s)	Date	Water-surface elevation (in feet above North American Vertical Datum of 1988)					
		Leonia (12305000) (CS 171.875)			Bonners Ferry (12309500) (CS 152.790)		
		Measured	Simulated	Difference	Measured	Simulated	Difference
5,000	03-10-03	1,804.58	1,804.72	-0.14	–	1,748.44	–
5,200	10-18-03	1,804.69	1,804.79	-.10	1,749.22	1,749.22	0.00
5,540	11-15-02	1,804.88	1,804.89	-.01	1,749.03	1,749.01	.02
10,700	01-02-04	1,807.19	1,807.18	.01	1,751.45	1,751.55	-.10
18,900	08-17-03	1,809.87	1,809.82	.05	1,754.80	1,754.84	-.04
20,900	07-02-03	1,810.43	1,810.47	-.04	1,756.88	1,756.97	-.09
21,200	12-14-03	1,810.51	1,810.50	.01	1,756.21	1,756.30	-.09
30,200	06-13-03	1,812.71	1,812.72	-.01	1,760.94	1,761.03	-.09
47,500	07-03-02	1,816.13	1,816.11	.02	1,765.66	1,765.71	-.05

Daily mean discharge (ft^3/s)	Date	Water-surface elevation (in feet above North American Vertical Datum of 1988)						
		Tribal Hatchery (12310100) (CS 149.910)			Klockmann Ranch (12314000) (CS 139.469)			Porthill (12322000) (CS 105.603)
		Measured	Simulated	Difference	Measured	Simulated	Difference	Measured
5,000	03-10-03	1,745.14	1,745.12	0.02	1,744.44	1,744.44	0.00	1,743.76
5,200	10-18-03	1,748.22	1,748.16	.06	1,747.80	1,747.78	.02	1,747.36
5,540	11-15-02	1,747.45	1,747.42	.03	1,746.93	1,746.91	.02	1,746.40
10,700	01-02-04	1,750.91	1,750.81	.10	1,750.03	1,749.99	.04	1,748.69
18,900	08-17-03	1,754.08	1,753.98	.10	1,752.52	1,752.58	-.06	1,749.58
20,900	07-02-03	1,756.31	1,756.31	.00	1,755.09	1,755.07	.02	1,752.61
21,200	12-14-03	1,755.54	1,755.52	.02	1,754.05	1,754.10	-.05	[1]1,751.19
30,200	06-13-03	1,760.35	1,760.41	-.06	1,758.92	1,758.92	.00	1,755.39
47,500	07-03-02	–	1,765.08	–	1,763.40	1,763.40	.00	1,758.66

[1] Water-surface elevation is estimated.

Differences in simulated and measured water-surface elevation were ±0.10 ft or less except for one value. Results from calibration are given in table 2. Manning's *n* values of the streambed only were adjusted during this process. Adjustments were made for the type of flow channel and streambed in each reach. Adjustments also were made equally to cross sections in each reach. The *n* values for the river banks were not adjusted and remained at 0.060. Table 3 shows the final *n* values for the four reaches. As generally accepted, *n* values in all four reaches decrease as discharge increases.

Simulated and measured velocities were compared using a three-parameter relation that can be viewed in a two-dimensional chart using lines of equal value to denote the third parameter. Figure 8 shows discharge in the study reach and water-surface elevation at Porthill gaging station on the coordinate axes, and average simulated velocity is denoted by a series of curved lines of equal value. The lines of equal value in this plot are unique because they represent simulated

Table 3. Calibrated Manning's *n* values (roughness coefficients) of streambed for four reaches, Kootenai River, Idaho.

[Locations of reaches are shown in figure 2. ft^3/s, cubic feet per second]

Daily mean discharge (ft^3/s)	Calibrated roughness coefficients of streambed for reaches between gaging stations			
	Leonia to Bonners Ferry	Bonners Ferry to Tribal Hatchery	Tribal Hatchery to Klockmann Ranch	Klockmann Ranch to Porthill
5,000	0.035	0.040	0.036	0.036
5,200	.035	.040	.036	.036
5,540	.035	.040	.036	.036
10,700	.050	.030	.032	.032
18,900	.044	.030	.030	.030
20,900	.043	.030	.030	.030
21,200	.0425	.030	.030	.030
30,200	.037	.027	.027	.027
47,500	.030	.020	.020	.020

average velocity distribution at cross section 149.910, and more than 150 groups of data triplets (each with three data points) were used to develop the plot.

Measured average velocities for water-surface elevations at the Tribal Hatchery gaging station (12310100) plotted closely to the lines of equal simulated average velocities (fig. 8). The similarity between measured and simulated average velocity (fig. 8) indicates that the model closely approximates the hydraulic response of the river system. Measured average velocities were obtained from discharge measurements using an acoustic Doppler current profiler (ADCP) at the gaging station. At high flows, however, discharge can not be measured at the Tribal Hatchery gaging station. Measured average velocities at high flows at the gaging station were computed by the following procedure: (1) transferring the value of discharge at the measurement site, (2) determining flow area at the gaging station from the average stage during the measurement using the stage-area relation at the gaging station, and (3) dividing the measured discharge by the flow area.

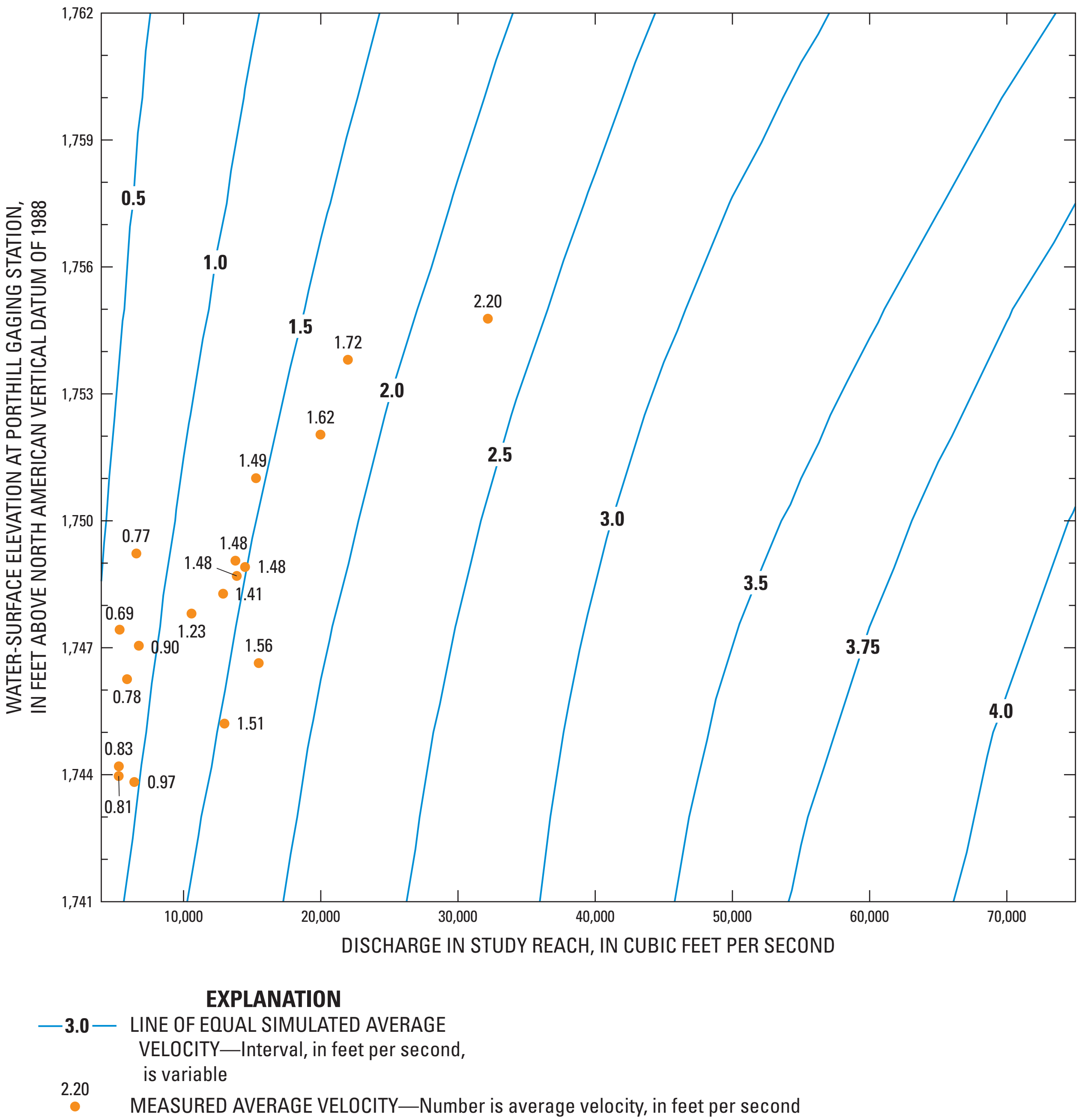


Figure 8. Measured and simulated average velocities at the Tribal Hatchery gaging station (12310100) (cross section 149.910) relative to discharge in the study reach and water-surface elevations at Porthill gaging station, Kootenai River near Bonners Ferry, Idaho.

Sensitivity Analyses

The sensitivity of the model to variations in Manning's *n* of the streambed and the river banks was determined by evaluating changes in simulated water-surface elevations as *n* was varied incrementally. The procedure involves holding all input parameters constant except the one being analyzed, varying that value and observing the results. Exact values of change from the sensitivity analysis should be viewed cautiously, but relative changes can provide insight as to how a particular input parameter may affect the results of the model. For all sensitivity simulations, the calibrated cross-section geometry was not changed.

Streambed

To determine the sensitivity of the model to variations in Manning's *n* of the streambed, a series of simulations at a discharge of 30,200 ft^3/s were made in which the *n*-value varied by ±10 percent of the initial calibrated values. The discharge of 30,200 ft^3/s was selected because it was near the greatest measured discharge of 32,200 ft^3/s at the Tribal Hatchery gaging station. For the 10-percent-decrease simulation, for example, *n* values in the reach from Klockmann Ranch to the Tribal Hatchery gaging stations were decreased from 0.027 to 0.024. For the 10-percent-increase simulation, *n* values were increased from 0.027 to 0.0297 for the Klockmann Ranch to Tribal Hatchery reach. The boundary conditions at the upstream and downstream cross sections were not changed.

Results of the sensitivity simulations to changes in *n*-values of the streambed for a discharge of 30,200 ft^3/s (table 4) indicated that the water-surface elevation is sensitive to the *n* value at this discharge. Varying *n* values by ±10 percent of the calibrated values resulted in changes in average water-surface elevation from about -0.8 ft to about 1.1 ft. Average differences for selected reaches for a discharge of 30,200 ft^3/s and average differences for the entire simulated reach (-0.62 to 0.74 ft) are shown in table 4. Average differences were largest at cross sections in the canyon-braided reaches. The largest differences of greater than 1 ft were at upstream cross sections near the Leonia gaging station. Average differences in the meander reaches were much smaller, and the smallest average differences (-0.25 to 0.26 ft) were at the reach below Klockmann Ranch gaging station (table 4). Differences in reaches upstream of the Tribal Hatchery were larger than the calibration limit (±0.15 ft); thus, the model is sensitive to changes in *n* values of the streambed.

River Bank

Sensitivity of the model to variations in Manning's *n* of the river bank was evaluated using a discharge of 47,500 ft^3/s because greater discharges would inundate a greater portion of the river banks and therefore affect more of the bank. The river bank is the portion of ground that borders the river to the top of the bank (start of flood plain).

Results of the sensitivity simulation to changes in *n* values of the river bank by ±10 percent were near the calibration limit of ±0.15 (table 5) and indicated that water-surface elevation was not sensitive to river bank *n* values. But because river bank *n* values may have greater uncertainty than ±10 percent, the sensitivity of the model to Manning's *n* values of the river bank was decreased to -50 percent (0.5 times) and increased to +150 percent (1.5 times) of the calibrated values.

Average differences between simulated and measured water-surface elevations were greater than the ±10-percent simulations (table 5) when the calibrated *n* values were adjusted to -50 percent and +150 percent. Average differences were greater than 1 ft in reaches upstream of the Tribal Hatchery. Average differences were smaller (-0.18 to 0.24 ft) in the reach below Klockmann Ranch. Average differences for the +150-percent simulation were about equivalent to the differences in the streambed. Overall, water-surface elevation differences were smaller for the river bank simulations than for the streambed simulations; thus, river bank differences were not as sensitive to changes in Manning's *n* as the streambed.

Table 4. Sensitivity of simulated water-surface elevation to changes in Manning's *n* (roughness coefficient) of streambed for a discharge of 30,200 cubic feet per second, Kootenai River, Idaho.

[Locations of reaches are shown in figure 2. Positive value is an increase in the simulated water-surface elevation as compared with the calibrated model; negative value is a decrease in the simulated water-surface elevation as compared with the calibrated model. ft^3/s, cubic foot per second]

Reach	Number of cross sections in each reach	Average difference in water-surface elevation, in feet, when Manning's *n* is changed by	
		–10 percent	+10 percent
Leonia to Bonners Ferry	58	–0.79	1.09
Bonners Ferry to Tribal Hatchery	16	–.75	.75
Tribal Hatchery to Klockmann Ranch[1]	46	–.65	.65
Klockmann Ranch to Porthill	36	–.25	.26
Entire model[1]	156	–.62	.74

[1]Excluding the Shorty Island side channel reach.

Table 5. Sensitivity of simulated water-surface elevation to changes in Manning's *n* (roughness coefficient) of the river banks for a discharge of 47,500 cubic feet per second, Kootenai River, Idaho.

[Locations of reaches are shown in figure 2. Positive value is an increase in the simulated water-surface elevation as compared with the calibrated model; negative value is a decrease in the simulated water-surface elevation as compared with the calibrated model. ft^3/s, cubic foot per second]

Reach	Number of cross sections in each reach	Average difference in water-surface elevation, in feet, when Manning's *n* is changed by			
		–10 percent	+10 percent	–50 percent	+150 percent
Leonia to Bonners Ferry	58	–0.16	0.18	–0.71	1.00
Bonners Ferry to Tribal Hatchery	16	–.21	.23	–.93	1.25
Tribal Hatchery to Klockmann Ranch[1]	46	–.16	.17	–.69	.92
Klockmann Ranch to Porthill	36	–.04	.04	–.18	.24
Entire model[1]	156	–.14	.15	–.60	.82

[1]Excluding the Shorty Island side channel reach.

Simulation of Hydraulic Characteristics of the Kootenai River

The model can be used to simulate changes in water-surface elevation, velocities, and other hydraulic characteristics resulting from changing river discharge and stage. For this study, the relations between three dependent model variables (three-parameter relations) were developed to show the effect of the riverine system. Three-parameter relations can be viewed in a two-dimensional chart using a series of curved lines to denote the third parameter.

Many model simulations were made to determine the response of the river to discharges in the study reach ranging from 4,000 to 75,000 ft^3/s, and water-surface elevations at the Porthill gaging station (12322000) ranging from 1,741 to 1,762 ft. These limits were selected because the discharge spans the range of calibration and recent measured values. The upper discharge limit of 75,000 ft^3/s was selected because it was about 1.5 times the highest calibrated discharge and about 2 times the greatest measured discharge. Discharge curves can be extrapolated two times beyond the greatest measured discharge (Rantz, 1982, p. 334).

Location of the Transition Between Backwater and Free-Flowing Water

Determining the location of the transition between backwater and free-flowing water (backwater extent) for various discharges in the study reach and water-surface elevations at Porthill gaging station was the primary objective of this study. Backwater extent can be easily determined for steady, uniform, mild-sloped channels, as illustrated in figure 3; in riverine systems where changes in channel geometry and slope occur, the use of computer models is needed to determine backwater extent.

The model was used to simulate backwater, free-flowing water, and normal-depth conditions in the Kootenai River. Then model simulations were compared, and the location of the transition between backwater and free-flowing water was determined by locating where water-surface elevations from the simulated backwater curve intersected the simulated normal-depth curve for each discharge and water-surface elevation.

The calibrated model was used without any modifications except for discharge in the study reach and water-surface elevation at the downstream boundary (Porthill) to simulate backwater and free-flowing water conditions in the study reach.

For normal-depth conditions, however, the calibrated model was extended according to the technique by Davidian (1984, p. 7) for discharges on very small slopes. The calibrated model for the Kootenai River was extended because streambed slopes are very small downstream of Bonners Ferry, Idaho. The model was extended to cross section 78.746 in British Columbia, Canada, about 27 mi downstream of Porthill, Idaho. Cross sections from Barton and others (2004) were used for this extension. The model was stopped at cross section 78.746 because this cross section is similar in width to upstream sections, whereas, the next downstream cross section (77.251) is several times wider and 30 ft shallower. However, this extension did not produce satisfactory results in the study reach, so the model was artificially extended farther downstream. Davidian (1984, p. 7) indicated that an artificially extended reach of 2,000 mi may be required to produce satisfactory results.

To create an artificially extended reach, Davidian (1984, p. 7) first indicated that the average streambed slope in the artificially extended reach be estimated from the thalwegs of the neighboring upstream cross sections. To facilitate this calculation, a locally weighted least-squares regression routine (LOWESS) was used to produce a smooth profile of thalwegs through the irregularly spaced cross sections. Thalwegs from all cross sections in the model were used in the LOWESS-smoothing routine. Results from the LOWESS-smoothing of thalwegs estimated a streambed slope of 6.218×10^{-5} ft/ft in the artificially extended reach; thus, this value was used.

Secondly, Davidian (1984, p. 7) indicated that cross-section shape in the artificially extended reach be estimated from averaging the neighboring upstream cross sections. Only the cross-sectional shape from cross section 80.675 (Barton and others, 2004, fig. 3*G*) was used in the artificially extended reach because graphical averaging of cross sections is time consuming and computer software is not available to perform this task. Cross section 80.675 also was similar in cross-sectional shape to upstream sections, whereas, downstream cross sections 78.746 and 77.251 (Barton and others, 2004, fig. 3*G*) were not similar.

Lastly, Davidian (1984) indicated that enough cross sections should be spaced in the artificially extended reach to spatially define water-surface elevations in the reach. Cross sections were located every 10 mi in the artificial extended reach, and provided adequate placement for model calculations. Manning's *n* values (roughness coefficients) from cross section 80.675 were used throughout the artificially extended reach.

An artificially extended reach of 200 mi downstream from cross section 78.746 was constructed but did not produce satisfactory results. A satisfactory result for the artificially extended reach is the convergence of two free-flowing (M_2) curves in the study reach that have a starting water-surface elevation of 1 ft or less apart from one another (Davidian, 1984). The model was then extended farther downstream and the results evaluated until satisfactory results were produced.

The artificial reach had to be extended 600 mi downstream from cross section 78.746 or 627 mi downstream from Porthill, Idaho, in order to produce satisfactory results. This artificially extended model was used to determine the normal-depth water-surface elevations at Porthill (cross section 105.603) given in table 6. These elevations in turn were used as starting water-surface elevations (Porthill) for simulating normal-depth conditions in the original calibrated model.

In the extended and artificially extended models, starting water-surface elevations at the downstream-most cross section were estimated from a slope-conveyance computation of normal depth using Manning's equation for open-channel flow. Water-surface elevations for these simulations are determined by channel shape and roughness coefficients, and thus, channel slope can be used to approximate the energy slope. A channel slope of 6.218×10^{-5} ft/ft was used in the artificially extended models to attain normal-depth conditions for any discharge.

Davidian (1984, p. 17) also indicated that the intersection of backwater curve with the normal-depth curves is acceptable when the backwater (M_1) depth is 1.03 times the normal depth. Multiplying normal depth by 1.03 causes both curves to intersect with one another, otherwise, the curves actually do not meet but approach or converge toward one another. Therefore, the location between backwater and free-flowing water was determined to occur at the intersection between the backwater curve and 1.03 times normal depth.

Normal-depth simulations were made using the calibrated model, using the normal-depth water-surface elevations from table 6, and using the same discharges as in the backwater and free-flowing water simulations. Simulations of the backwater and free-flowing water and normal-depth water-surface elevations were compared at the same discharge to determine where flow changed from backwater to free-flowing water conditions.

These results were used to develop a three-parameter relation—discharge in the study reach and water-surface elevation at Porthill on the coordinate axes, and location of the transition between backwater and free-flowing water by a series of curved lines of equal value, as shown in figure 9. More than 100 groups of data triplets (each with three data points) were used to develop the plot. River mile 105.6 in figure 9 is at the International Boundary between Canada and United States near Porthill, Idaho and RM 153 is about 1,000 ft upstream of U.S. Highway 95 Bridge. Various combinations of discharge in the study reach and water-surface elevation at Porthill were used in the model to determine the location of the transition between backwater and free-flowing water that ranged from Porthill (RM 105.6) to about RM 158 at Crossport, a span of about 52 mi. The transition between

Table 6. Simulated normal-depth water-surface elevations at Porthill (cross section 105.603), Kootenai River, Idaho.

[NAVD 88, National Vertical Datum of 1988. ft^3/s, cubic foot per second; ft, foot]

Simulated discharge (ft^3/s)	Simulated normal-depth water-surface elevations (in ft above NAVD 88)
4,000	1,727.41
5,000	1,728.62
10,000	1,732.91
15,000	1,736.14
20,000	1,738.91
25,000	1,741.51
30,000	1,744.24
35,000	1,746.61
40,000	1,748.85
45,000	1,750.70
50,000	1,753.16
55,000	1,757.10
60,000	1,760.41
65,000	1,762.91
70,000	1,765.26
75,000	1,767.59

backwater and free-flowing water stays at about the same river mile for a number of simulated discharges from RM 153 through RM156 (fig. 9). For example, at a water-surface elevation of 1,750 ft, the transition stays at about RM 155.9 for discharges ranging from 13,000 to 30,000 ft^3/s. The area of transition between RM 141.6 and RM 149 (reach where sturgeon mostly spawn) is quite narrow (fig. 9).

Paired data comprised of discharge in the study reach and water-surface elevation at the Porthill gaging station were only available for 1989-2003 because no stage data were available prior to 1989. Discharge in the study reach for 1989 through 2002 was calculated by subtracting the discharge at the Porthill gaging station from discharge at Boundary Creek gaging station. For 2003, discharge for the Tribal Hatchery gaging station was used.

The measured data indicate that the location of the transition between backwater and free-flowing water in the study reach extended from RM 152 (downstream of Bonners Ferry) to RM 157 (near Crossport), a 5-mile span. The average backwater location from measured data was at about RM 154 (several miles upstream of Bonners Ferry). Measured data pairs located downstream of RM 150 (fig. 9) probably represent conditions where the water-surface elevation and (or) discharge were varying quite rapidly in the study reach. Measured data pairs located between RM 141.6 and RM 149 (where sturgeon mostly spawn) also had water-surface elevations and (or) discharges that were varying. Figure 9 cannot be used when the water-surface elevation and (or) discharge are varying in the study reach. An example of the usage of figure 9 (a three-parameter relation) is given in section "Real-Time Application."

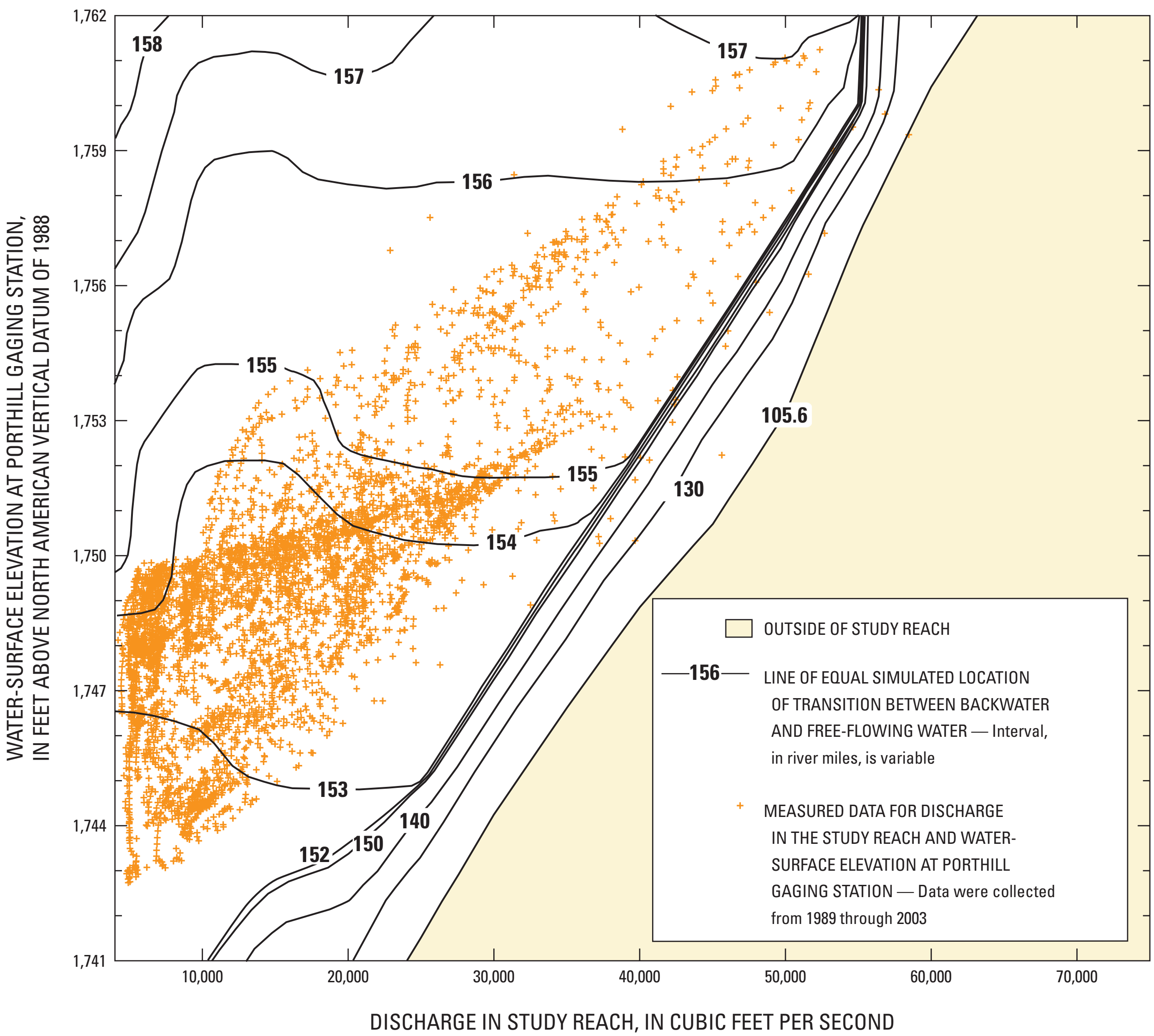


Figure 9. Simulated location of transition between backwater and free-flowing water in river miles relative to discharge in the study reach and water-surface elevations at Porthill gaging station, Kootenai River near Bonners Ferry, Idaho.

Other Three-Parameter Relations

Three-parameter relations also were developed for discharge in the study reach and water-surface elevation at Porthill gaging station on the coordinate axes and two other variables—simulated discharge through the Shorty Island side channel (fig. 10) and simulated average velocity at selected cross sections (fig. 11).

Simulated discharge in the Shorty Island side channel ranged from 0 to more than 8,000 ft^3/s, depending on discharge in the study reach and water-surface elevation at Porthill gaging station (fig. 10). The series of curved lines of equal value in figure 10 represent simulated discharge in the Shorty Island side channel. The shaded region in figure 10 is the region of measured data shown in figure 9, excluding unsteady data.

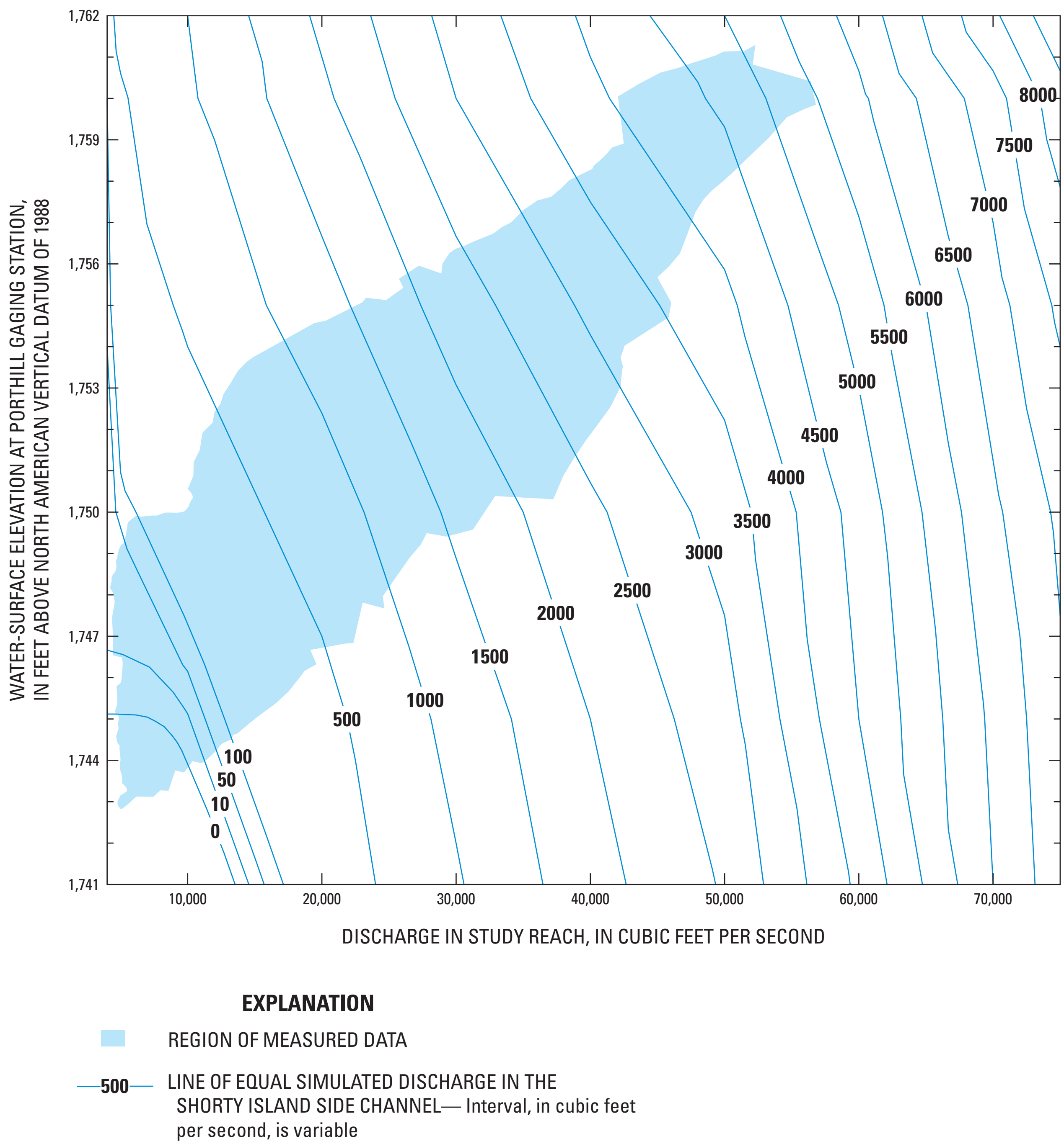


Figure 10. Simulated discharge for the Shorty Island side channel relative to discharge in the study reach and water-surface elevations at Porthill gaging station, Kootenai River near Bonners Ferry, Idaho.

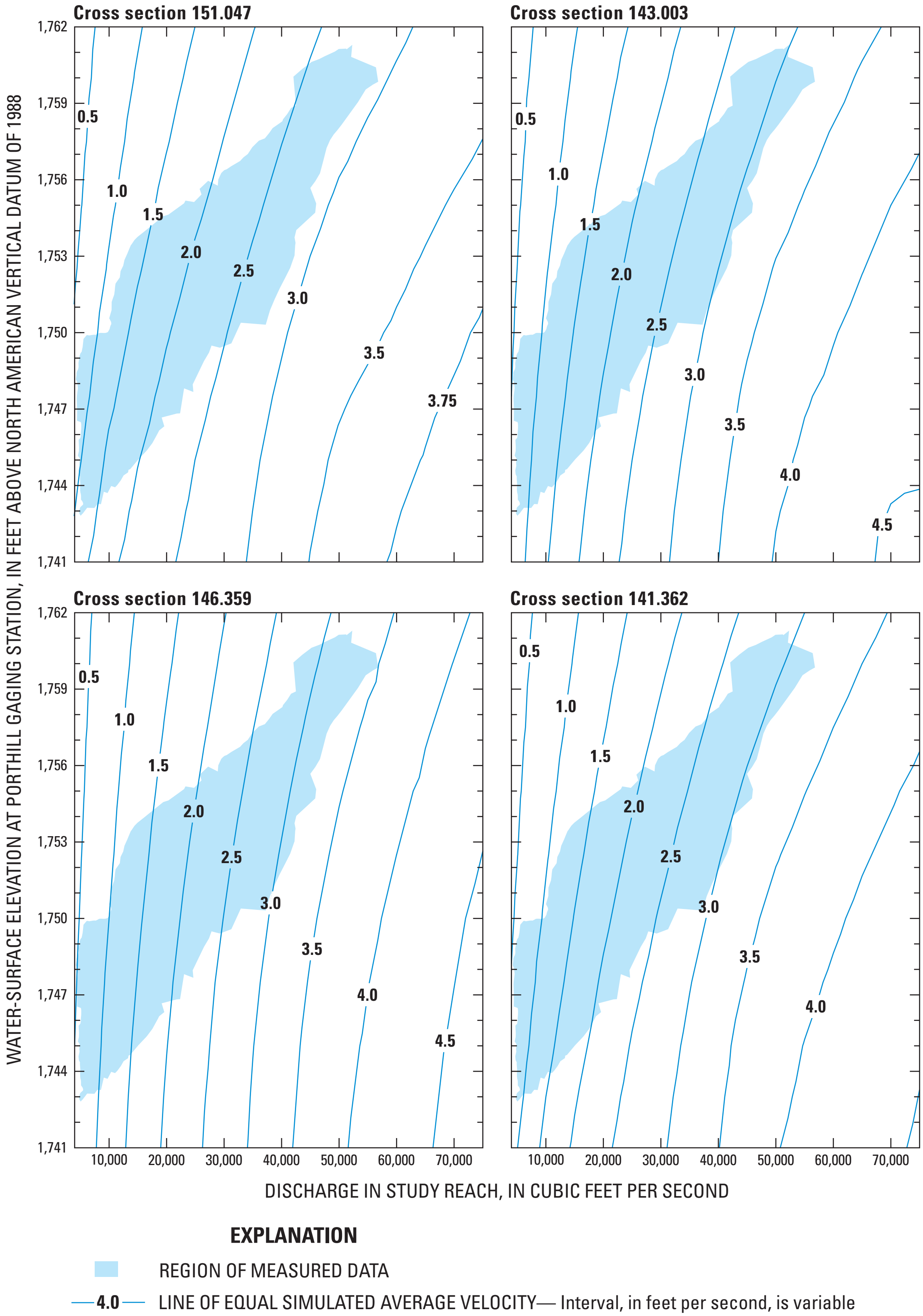


Figure 11. Simulated average velocity for selected cross sections relative to discharge in the study reach and water-surface elevations at Porthill gaging station, Kootenai River near Bonners Ferry, Idaho.

For the shaded region, simulated discharge for Shorty Island ranged from 0 to about 5,500 ft^3/s. The non-shaded regions in figure 10 show combinations of discharge in the study reach and water-surface elevations at Porthill that were not measured during 1989–2003.

Simulated average velocity at five cross sections ranged from about 0.5 to about 4 ft/s depending on discharge in the study reach and water-surface elevation at Porthill (figs. 8 and 11). The series of curved lines in figures 8 and 11 represent the simulated average velocity. However, simulated average velocity distribution (three-parameter relation) of each of the five cross sections is unique. Again, the measured region (shaded region in figure 11) is represented on the coordinate axes. For the shaded region, simulated average velocity ranged from 0 to about 3.5 ft/s. The non-shaded regions in figure 11 shows combinations of discharge in the study reach and water-surface elevations at Porthill that have not been observed during 1989–2003, but this does not indicate that these conditions are impossible.

Other hydraulic, sediment/incipient motion, ecological, and biological variables also can be displayed in a similar method as shown in figures 8 through 11. For example, the three-parameter relation in figure 11 can be developed for any cross section. These three-parameter relations also can be displayed longitudinally. Temperature and sturgeon spawning locations can be used in these three-parameter relations.

Real-Time Application

The following example shows how model results were used to predict the location of transition between backwater and free-flowing water if the current conditions are known. Discharge through the Shorty Island side channel and average velocity at selected cross sections also can be predicted.

Data from two telemetered gaging stations in the study reach, Tribal Hatchery (12310100) and Porthill (12322000), provide real-time data to use in this process. These gaging stations transmit real-time stage data from the gaging station and index velocity data from the ADVM by satellite to the USGS database in Boise, Idaho. The database checks the data and computes discharge using a stage-area relation and an index velocity-average velocity relation. For more information about the procedure, relations, and computation, the reader is directed to Morlock and others (2002). Discharge and stage data for these gaging stations are accessible from the Idaho USGS Web page, http://idaho.usgs.gov/.

To predict the location of transition between backwater and free-flowing water:

1. Go to the list of streamgages at Idaho USGS Web page (URL: http://waterdata.usgs.gov/id/nwis/current/?type=flow) and note the river stage at Kootenai River at Porthill gaging station (12322000) and discharge at Kootenai River at Tribal Hatchery, near Bonners Ferry gaging station (12310100). For example, on October 10, 2004, at 1221 hours (12:21 pm) Mountain Standard Time, the river stage at Porthill (station 12322000) was 44.77 ft, and discharge at Tribal Hatchery (station 12310100) was 6,500 ft^3/s.

2. Add 1,703.89 ft (table 1) to the stage at Porthill (44.77 ft + 1,703.89 ft = 1,748.66 ft) to calculate the water-surface elevation at Porthill in NAVD 88 datum.

3. Plot these values on figure 9 using the coordinate axes, and note their intersection as shown in figure 12. If the intersected point does not land on a line of equal river miles as shown in figure 12, the user will need to interpolate between the lines of equal river miles to estimate the point's river mile value. For a stage of 1,748.66 ft and discharge of 6,500 ft^3/s, the point intersected between RM 153 and RM 154. By interpolating between the lines of equal river miles, the location of the point occurs at about RM 153.9.

4. To visualize its spatial location, plot the interpolated river mile value of the point on a map that has river miles such as figure 2. The location of RM 153.9, upstream of Bonners Ferry, is shown on the aerial photograph in figure 13.

In a similar procedure, the other three-parameter relations can be used to estimate discharge in the Shorty Island side channel (using figure 10) and average velocity at selected cross sections (using figures 8 and 11) for a known water-level elevation at Porthill gaging station and discharge at the Tribal Hatchery gaging station.

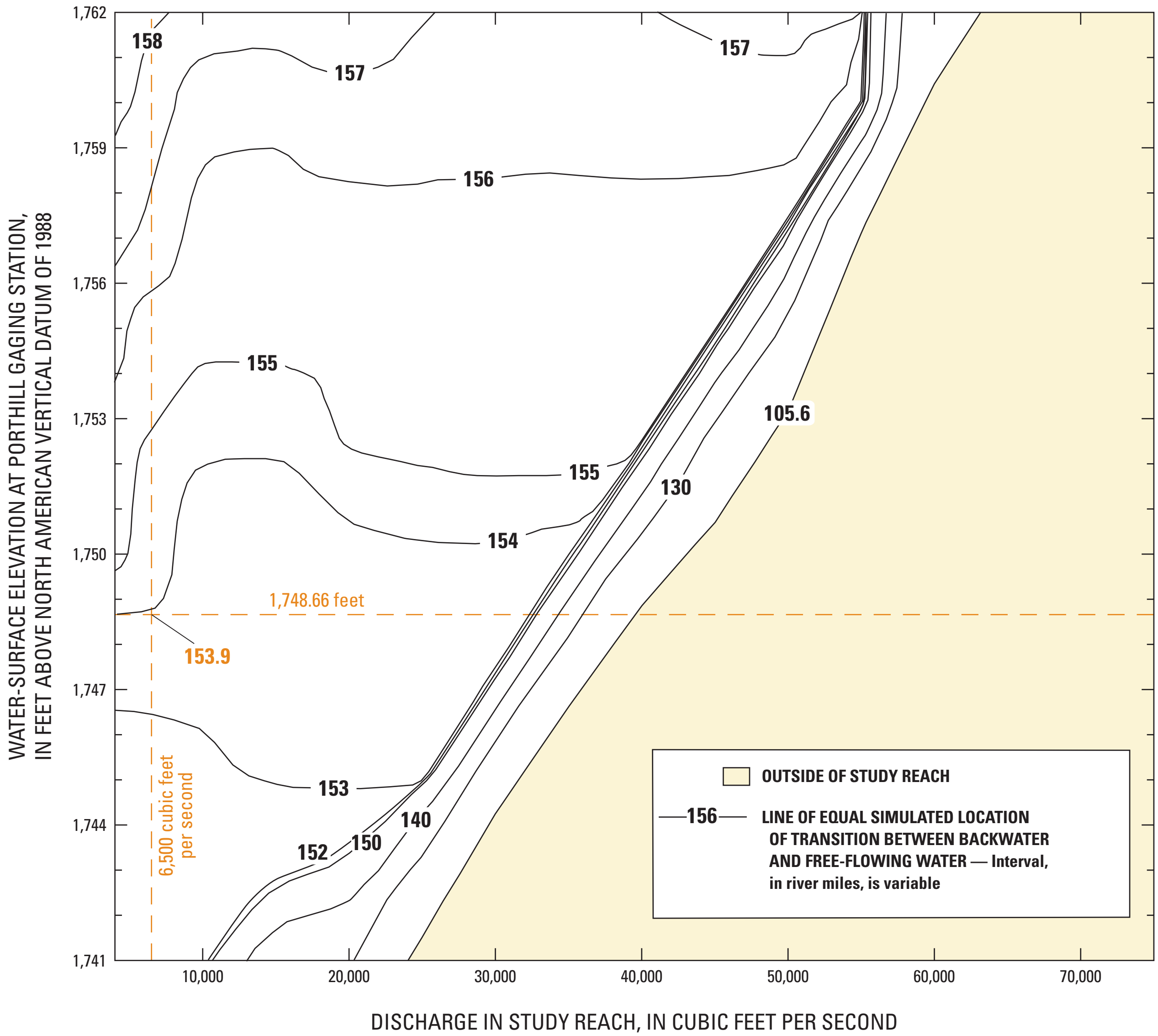


Figure 12. Simulated location of transition between backwater and free-flowing water for a real-time event, October 10, 2004, Kootenai River near Bonners Ferry, Idaho.

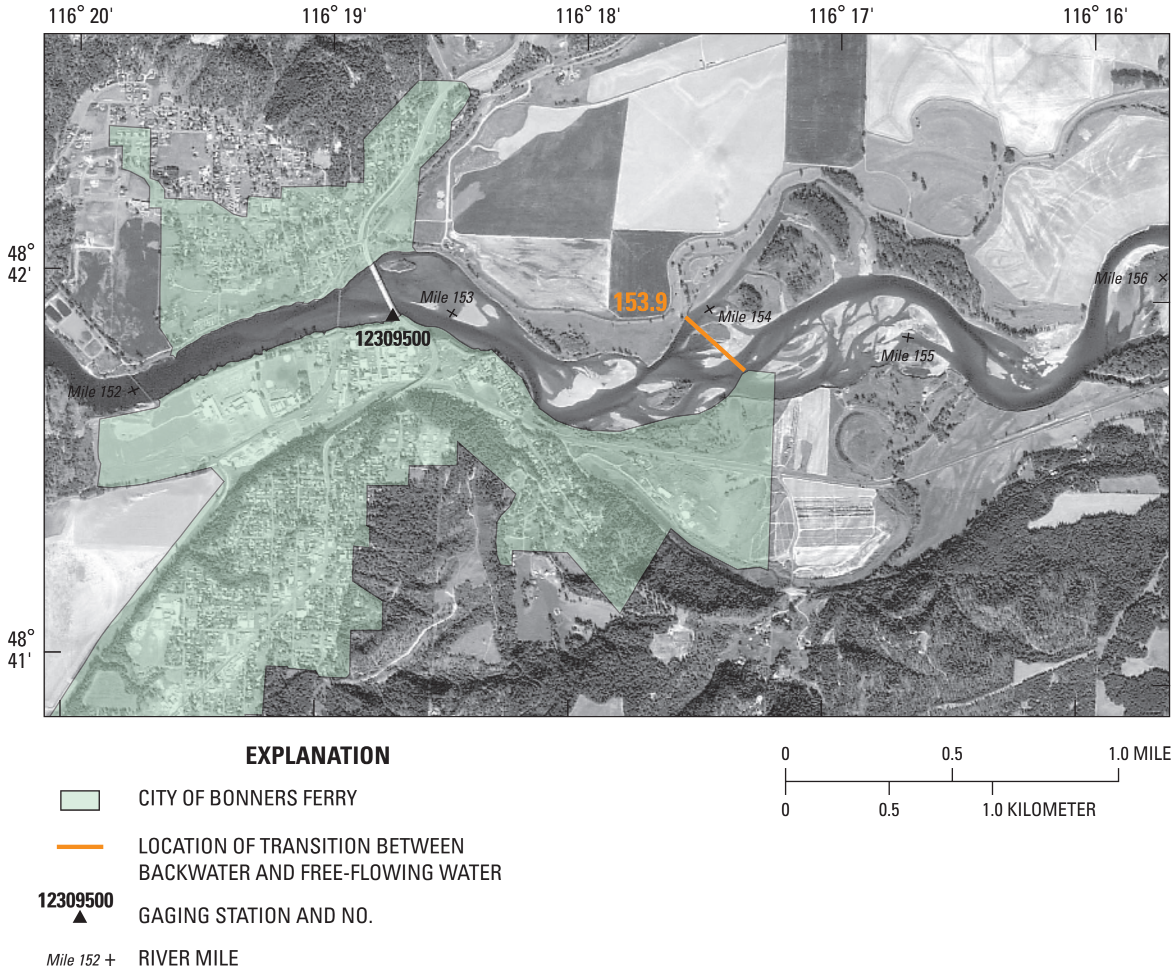


Figure 13. Location of the simulated transition between backwater and free-flowing water for a real-time event, October 10, 2004, Kootenai River near Bonners Ferry, Idaho.

Limitations of the Model

When using the model, it is important to realize the limitations of the model. A digital model can be a useful tool for predicting various hydraulic characteristics in response to changes in the riverine system. However, the accuracy with which a model can simulate water-surface elevations, velocity, and extent of backwater is directly related to the accuracy and adequacy of the input data used to calibrate the model.

The computer model, HEC-RAS, incorporates many simplifying assumptions about the riverine system. Most important are the assumptions of one-dimensional, gradually varied, and steady flow. These simplifications might allow the model to simulate water-surface elevations with discharges greater than or less than would be experienced under actual conditions in the study area. This model successfully simulates water-surface elevations in the Kootenai River for its intended purpose, even though it is unable to account for (1) uneven velocities in a cross section especially in curved sections at bends, (2) uneven water-surface elevations in a cross section, (3) scour and fill and sediment transport in a cross section, (4) infiltration losses and (or) gains in the channel, and (5) other aspects of the actual river discharge in the Kootenai River.

Considerable uncertainty is associated with how velocity and shear stress are distributed throughout the study reach. These uncertainties cannot be addressed by a one-dimensional model like HEC-RAS. Multiple-dimensional models that would compute the discharge and velocity field more precisely are needed to refine velocity and shear stress distributions of the Kootenai River in the study reach. HEC-RAS was considered sufficient to provide reasonable results in meeting the objectives of this study.

Verification of the values of Manning's *n* (roughness coefficients) throughout the modeled reach is needed, especially for a wide range of hydraulic and discharge conditions. Manning's *n*-verification measurements were not available for the study reach. If these measurements were available, they would permit refinement of the model, especially in the reaches between each of the gaging stations or in the spawning reach.

Summary

The Kootenai River originates in British Columbia, Canada, and flows southward into Lake Koocanusa in British Columbia and Montana. From there, the river flows westward through Montana and Idaho until it meets Deep Creek near Bonners Ferry, Idaho. Then the river flows in a northerly direction from Deep Creek to where it empties into Kootenay Lake. From Kootenay Lake, it flows westward to its confluence with the Columbia River. The study reach is 65.6 miles in length starting at the Leonia gaging station and ending at the Porthill gaging station. The study reach also includes an approximately 1-mile-long side channel around the western side of Shorty Island. Streamflow in the river has been substantially altered by dams and levees, which may negatively influence the spawning of the Kootenai River white sturgeon. The population of white sturgeon has been decreasing and was listed as an Endangered Species in 1994.

In the study reach, the Kootenai River is characterized by a canyon reach, a braided reach, and a meander reach. The canyon reach extends from the Leonia gaging station to about Crossport and is characterized by a long straight channel, and steep canyon walls. The braided reach has many exposed islands and (or) bars that divide the river into multiple channels especially at low flows, and the streambed is composed primarily of gravels and cobbles. This reach extends from near Crossport to the U.S. Highway 95 Bridge at Bonners Ferry. The meander reach is a single channel with gentle bends. Downstream of Ambush Rock near Bonners Ferry, the streambed is composed primarily of sand. Sturgeons spawn in the meandering reach primarily between river mile (RM) 141.6 and RM 149.0, which is considered an inferior spawning habitat because of the sands and low-flow velocities. Spawning in this area possibly is linked to the sturgeons reacting to hydraulic conditions caused by changes in Kootenay Lake levels and flows in the river primarily controlled by Libby Dam.

A one-dimensional hydraulic-flow model of the study reach, which includes the white sturgeon spawning reach, was developed to aid evaluating the reach’s hydraulic characteristics. The model was composed of 164 cross sections, most of which came from a previous river survey-conducted in 2002–03. The model was calibrated to water-surface elevation and discharge data from four gaging stations. Model calibration was considered acceptable when the difference between simulated and measured water-surface elevations was ±0.15 foot or less. Actual differences were ±0.10 foot or less except for one value. Average measured and average simulated velocities were compared at one gaging station. This comparison indicated that average simulated velocities closely matched average measured velocities.

The calibrated model was used to determine the location of the transition between backwater and free-flowing water. Normal-depth and backwater simulations were compared, and the location was determined by where water-surface elevations intersected one another. Discharge in these simulations ranged from 4,000 to 75,000 cubic feet per second (ft^3/s), about 1.5 times the highest calibrated discharge. Water-surface elevations at Porthill gaging station ranged from 1,741 to 1,762 feet. Model results were presented by a three-parameter relation where discharge in the study reach and water-surface elevation at the Porthill gaging station appear on the coordinate axes, and the location between backwater and free-flowing water in river miles is denoted by a series of curved lines. Measured data pairs (discharge in study reach and water-surface elevation at Porthill gaging station) from 1989 through 2003 also were shown with the three-parameter relations. Most of the time, the location of the transition between backwater and free-flowing water for the measured data occurred between RM 152 downstream of Bonners Ferry and RM 157 (near Crossport). The average location was at about RM 154.

Other three-parameter relations were developed for determining discharge in the Shorty Island side channel and determining average velocity at selected cross sections. For these relations, the coordinate axes were not changed, only the third parameter (discharge in the side channel and average velocity) was changed. Simulated discharge in the side channel ranged from 0 to more than 8,000 ft^3/s. Relations of simulated average velocity at five cross sections in the white sturgeon spawning reach also were developed. These relations indicate that simulated average velocity ranged from about 0.5 foot per second (ft/s) to about 4.0 ft/s in the cross sections. Relations using other hydraulic, sediment/incipient motion, ecological and biological characteristics also could be developed using a similar procedure.

These three-parameter relations can be used in real time by accessing discharge and stage data from the Idaho USGS Web page (URL: http://waterdata.usgs.gov/id/nwis/current/?type=flow). Stage and stream velocity data from the Tribal Hatchery and Porthill gaging stations are transmitted in real-time by satellite to USGS computers to compute discharge. The coordinate axes of the three-parameter relations use discharge from the Tribal Hatchery gaging station and water-surface elevations from the Porthill gaging station. Therefore, the location of the transition between backwater and free-flowing water, discharge in Shorty Island side channel, and (or) average velocity at selected cross sections can be determined for the current conditions.

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Glossary

backwater: Water backed up or retarded in its course as compared with its normal or free-flowing condition of flow. Backwater is an increase in upstream flow depth due to a constriction in a channel, change in channel slope, or change in roughness. Backwater is denoted by hydraulic engineers as an M_1 curve.

channel: The channel includes the thalweg and streambed.

confluence: The flowing together of two or more streams; the place where a tributary joins the main stream.

conveyance: A measure of the carrying capacity of a channel section and is directly proportional to channel discharge. Conveyance is that part of Manning's equation that excludes the square root of the energy gradient or friction slope.

cross section: A series of coordinate pairs of elevation and stationing that describes the channel shape perpendicular to the mean flow direction.

flood: Any relatively high streamflow that overtops the natural or artificial banks of a river.

floodplain: Land adjoining (or near) the channel of a watercourse which has been, or may be, covered by floodwaters. A flood plain functions as a temporary channel or reservoir for overbank flows. The lowland that borders a river and is usually dry but subject to flooding.

free-flowing water: Water that is not backed up or retarded in its course. Free-flowing water is denoted by hydraulic engineers as an M_2 or M_3 curve.

high-water marks: Evidence of the stage reached by a flow. High-water marks generally consist of debris, scour marks, or staining of rocks found along the channel banks.

hydrograph: A graph of stage or discharge versus time.

LOWESS smoothing: A robust, locally weighted regression method to smooth data. A locally weighted polynomial regression is fit to each point and nearby points. This method also is referred as LOESS smoothing. The smoothed data provides a clearer shape of the relation between the independent and dependent variables.

Manning's roughness coefficient (*n* values) or Manning's *n*: A measure of the frictional resistance exerted by a channel on the flow. The *n* value also can reflect other energy losses such as those resulting from the transport of material and debris, unsteady flow, extreme turbulence, that are difficult or impossible to isolate and quantify.

normal depth: The depth of flow for a given discharge, fixed channel shape, slope, and roughness.

reach: A length of stream that is chosen to represent a uniform set of physical, chemical, and biological conditions.

river bank: The sloping ground that borders a stream and confines the water in the channel. It is bordered by the floodplain and channel.

runoff peak flow: The largest value of the runoff flow, which occurs during a flood, as measured at a particular point in the drainage basin.

slope: The change in elevation per unit change in the channel's length.

stage: The height of a water surface above gage datum; same as gage height.

stage-discharge relation: The relation between the water-surface elevation and discharge.

steady flow: Discharge and depth of flow does not change with time or during a selected period of time.

streamflow, discharge, or flow: A general term for water flowing through a channel.

subcritical flow: If the flow is subcritical, flow depth is greater than the flow depth in critical flow. Inertial forces are less than the gravitational forces.

thalweg: A line connecting the lowest points along the length of a riverbed. It can be quite sinuous and wander within the channel.

water-surface curves or profile: Longitudinal plots of the water-surface elevation as a function of distance downstream through a channel reach.

water-surface elevation: Height of a water surface above a datum; same as adding stage and NAVD 88 datum for example.

velocity-stage-discharge relation: Relation between velocity, water-surface elevation, and discharge.

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Berenbrock

Simulation of Hydraulic Characteristics in the White Sturgeon Spawning Habitat of the Kootenai River near Bonners Ferry, Idaho

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