In cooperation with the Bureau of Reclamation

Relation between Streamflow of Swiftcurrent Creek, Montana, and the Geometry of Passage for Bull Trout (*Salvelinus confluentus*)

Scientific Investigations Report 2009–5100

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

Cover: Elizabeth Reynolds measuring cross-sectional topography of Swiftcurrent Creek, Montana, in September, 2007.

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Conversion Factors

We use mixed measurement units in this report—dominantly SI (metric) but report discharge in cubic feet per second (ft^3/s) to facilitate interpretation by the water resource interests and managers.

Inch/Pound to SI

Multiply	By	To obtain
	Length	
inch (in.)	2.54	centimeter (cm)
foot (ft)	0.3048	meter (m)
mile (mi)	1.609	kilometer (km)
yard (yd)	0.9144	meter (m)
	Area	
square mile (mi^2)	2.590	square kilometer (km^2)
	Flow rate	
cubic foot per second (ft^3/s)	0.02832	cubic meter per second (m^3/s)

SI to Inch/Pound

Multiply	By	To obtain
	Length	
centimeter (cm)	0.3937	inch (in.)
meter (m)	3.281	foot (ft)
kilometer (km)	0.6214	mile (mi)
meter (m)	1.094	yard (yd)
	Area	
square kilometer (km^2)	0.3861	square mile (mi^2)
	Flow rate	
cubic meter per second (m^3/s)	35.31	cubic foot per second (ft^3/s)

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

Horizontal coordinate information is referenced to North American Datum of 1983 [1999] (NAD 83 [99]).

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

Relation between Streamflow of Swiftcurrent Creek, Montana, and the Geometry of Passage for Bull Trout (*Salvelinus confluentus*)

By Gregor T. Auble,[1] Christopher L. Holmquist-Johnson,[1] Jim T. Mogen,[2] Lynn R. Kaeding,[2] and Zachary H. Bowen[1]

Executive Summary

1. Operation of Sherburne Dam in north-central Montana has typically reduced winter streamflow in Swiftcurrent Creek downstream from the dam and resulted in passage limitations for bull trout (*Salvelinus confluentus*), which is a federally listed threatened fish.

2. We defined an empirical relation between discharge in Swiftcurrent Creek between Sherburne Dam and the downstream confluence with Boulder Creek and fish passage geometry by considering how the cross-sectional area of water changed as a function of discharge at a set of 26 “bottleneck” cross sections likely to limit fish passage.

3. We measured channel topography and water-surface elevations at specific discharges across the 26 cross sections by using survey-grade Global Positioning System equipment during September 18–September 22, 2007; June 2–June 7, 2008; and September 11–September 13, 2008. We scored each cross section according to the extent to which a cross-sectional area of water provided a minimum passage window of 15 by 45 centimeters, summarized the distribution of passability among cross sections as a function of discharge, and examined the sensitivity of results to variation in the size of the minimum passage window.

4. Passage geometry at the “bottleneck” cross sections increased strongly with discharge over the range of 1.2 to 24 cubic feet per second (ft^3/s). Most of these cross sections did not satisfy the minimum (15 by 45 cm) passage criteria at 1.2 ft^3/s (median passable width of 0); 25 percent of these cross sections had no passage at 12.7 ft^3/s, whereas at 24 ft^3/s all but one of the cross sections had some passage, and 90 percent had more than 3 meters of width satisfying the minimum passage criteria. Combining these results with estimates of natural streamflow in the study reach further suggests that natural streamflow provided adequate passage at some times in most months and locations in the study reach, although not for all individual days and locations.

5. Limitations of our analysis include assumptions about minimum passage geometry, measurement error, limitations of the cross-sectional model we used to characterize passage, the relation of Sherburne Dam releases to streamflow in the downstream study reach, and the relation of passage geometry as we have measured it to fish responses of movement and stranding.

6. Our sensitivity analysis suggests that the overall results are not highly dependent on exact dimensions of the minimum passage window: (a) passage is somewhat more sensitive to minimum depth than minimum width; (b) substantial (40 percent) increases in the dimensions of the minimum passage window still result in widespread (25th percentile of “bottleneck” cross sections) passage at 24 ft^3/s; and (c) substantial decreases in minimum passage dimensions (20 or 40 percent of depth or 40 percent of width) might move the discharge required to provide widespread passage down from 12.7–24 ft^3/s to less than 12.7 ft^3/s.

7. Finally, our results, which indicate adequate passage at 12.7–24 ft^3/s, are limited to the physical geometry of passage in relation to streamflow in the absence of ice cover. Fish will be trapped in pool locations in the absence of adequate passage geometry. Adequate passage geometry, however, does not guarantee that fish will move out of pools, nor does it address whether fish will or will not survive in pool locations at different water depths, ice thicknesses, flow rates, oxygen levels, or predation pressures. Implications of our results for specific individual and population responses of fish may require additional studies, perhaps including adaptive management, especially focused on winter conditions with ice cover.

[1] U.S. Geological Survey, Fort Collins, Colorado

[2] U.S. Fish and Wildlife Service, Montana Branch of Native Fishes Management, Bozeman, Montana

Introduction

Purpose

This work was undertaken to define an empirical relation between streamflow in Swiftcurrent Creek, a tributary to the St. Mary River in north-central Montana, and the relative availability of physical passage for bull trout along Swiftcurrent Creek.

Need

Operation of Sherburne Dam in north-central Montana strongly determines streamflow in Swiftcurrent Creek downstream from the dam. Typically, water has been stored in Sherburne Lake during nonirrigation months (fall through spring) for subsequent use during irrigation season (approximately April through September). There has commonly been little or no streamflow in the reach of Swiftcurrent Creek between the dam and the confluence with Boulder Creek while the dam is closed (fig. 1).

Bull trout (*Salvelinus confluentus*), whose natural range extends from northern areas of California and Nevada to upstream regions of the Yukon River basin in Alaska and Canada, are federally listed as a threatened fish species (U.S. Fish and Wildlife Service, 1999). Bull trout occur east of the Continental Divide in portions of the Mackenzie, upper Peace, Athabasca, North Saskatchewan, and South Saskatchewan River basins—including the Montana portion of the South Saskatchewan River basin that contains Swiftcurrent Creek in the St. Mary drainage (Cavender, 1978; Haas and McPhail, 1991; Nelson and Paetz, 1992). Barriers to fish movement due to construction and operation of dams and other water-management facilities were considered important causes of population decline in the original designation of threatened status (U.S. Fish and Wildlife Service, 1999). Routine curtailment of fall and winter discharge in Swiftcurrent Creek downstream from Sherburne Dam has been implicated in the observed over-winter mortality of two radio-tagged bull trout in Swiftcurrent Creek, possibly due to suffocation, predation, or other factors associated with the fish being stranded in shallow, isolated pools (Mogen and Kaeding, 2005b). Thus, defining the relation between discharge in Swiftcurrent Creek downstream from Sherburne Dam and the availability of passage for fish in this reach is useful to inform decisions about possible minimum releases from Sherburne Dam.

Scope

In cooperation with the Bureau of Reclamation, we quantified a relation between discharge in Swiftcurrent Creek and fish passage geometry by considering how the cross-sectional area of water changed as a function of discharge at a number of locations (“bottleneck” cross sections) likely to limit fish passage. Defining a minimum passable window (15 cm tall by 45 cm wide) allowed each cross section to be evaluated in terms of how much, if any, passage was available at a given discharge. Field measurements of the topographic surface at each cross section and measurement of water-surface elevations at multiple discharges were used to quantify the relation between passage geometry and discharge empirically. We further examined the sensitivity of this relationship to different assumptions about the dimensions of the minimum passable window.

Study Area

Our study reach is the section of Swiftcurrent Creek downstream from the outlet structure of Sherburne Dam to the confluence with Boulder Creek (fig. 1). The straight-line distance between these points is 4,530 m, and the thalweg distance of the main channel is approximately 5,340 m, producing an overall sinuosity of 1.18. Sherburne Dam is a 29-m-tall earthen dam, constructed between 1914 and 1921, impounding Sherburne Lake on Swiftcurrent Creek (Bureau of Reclamation, 2008). National Geodetic Survey (NGS) benchmark PID–AI7862 (National Geodetic Survey, 2007) on the current concrete outlet structure at the base of the dam has an altitude of 1,445.6 m (NAVD88). Our measurements of thalweg elevations from near the dam to the confluence with Boulder Creek indicate an overall stream gradient of 4.4 m/km. Stream substrate is dominantly cobble and gravel with finer textured material in some pools.

Trapping, electrofishing, and radiotelemetry studies of bull trout in the St. Mary River basin between 1997 and 2003 identified both migratory and nonmigratory populations and confirmed some of the negative effects of water-management structures and operations on fish (Mogen and Kaeding, 2005a,b). These effects include blocked passage of adult bull trout during irrigation season by the St. Mary Diversion Dam (Mogen and Kaeding, 2005b), entrainment of fish into the St. Mary Canal (Mogen and Kaeding, unpub. data), and stranding of fish in Swiftcurrent Creek (Mogen and Kaeding, 2005b). Active winter searches for radiotagged fish found bull trout tagged in Boulder Creek present in St. Mary River, lower St. Mary Lake, in Swiftcurrent Creek downstream from Boulder Creek, in Boulder Creek, and in Swiftcurrent Creek between Sherburne Dam and Boulder Creek (Mogen and Kaeding, 2005b). Four of the 15 winter contacts with Boulder Creek-tagged bull trout in Swiftcurrent Creek between Sherburne Dam and Boulder Creek were in deep pools within or immediately downstream from the Sherburne Dam outlet structure. The mortality of two radiotagged bull trout was associated with stranding in Swiftcurrent Creek (Mogen and Kaeding, (2005b).

Streamflow in Swiftcurrent Creek between Sherburne Dam and the confluence with Boulder Creek is significantly affected by operation of the dam as a storage facility within

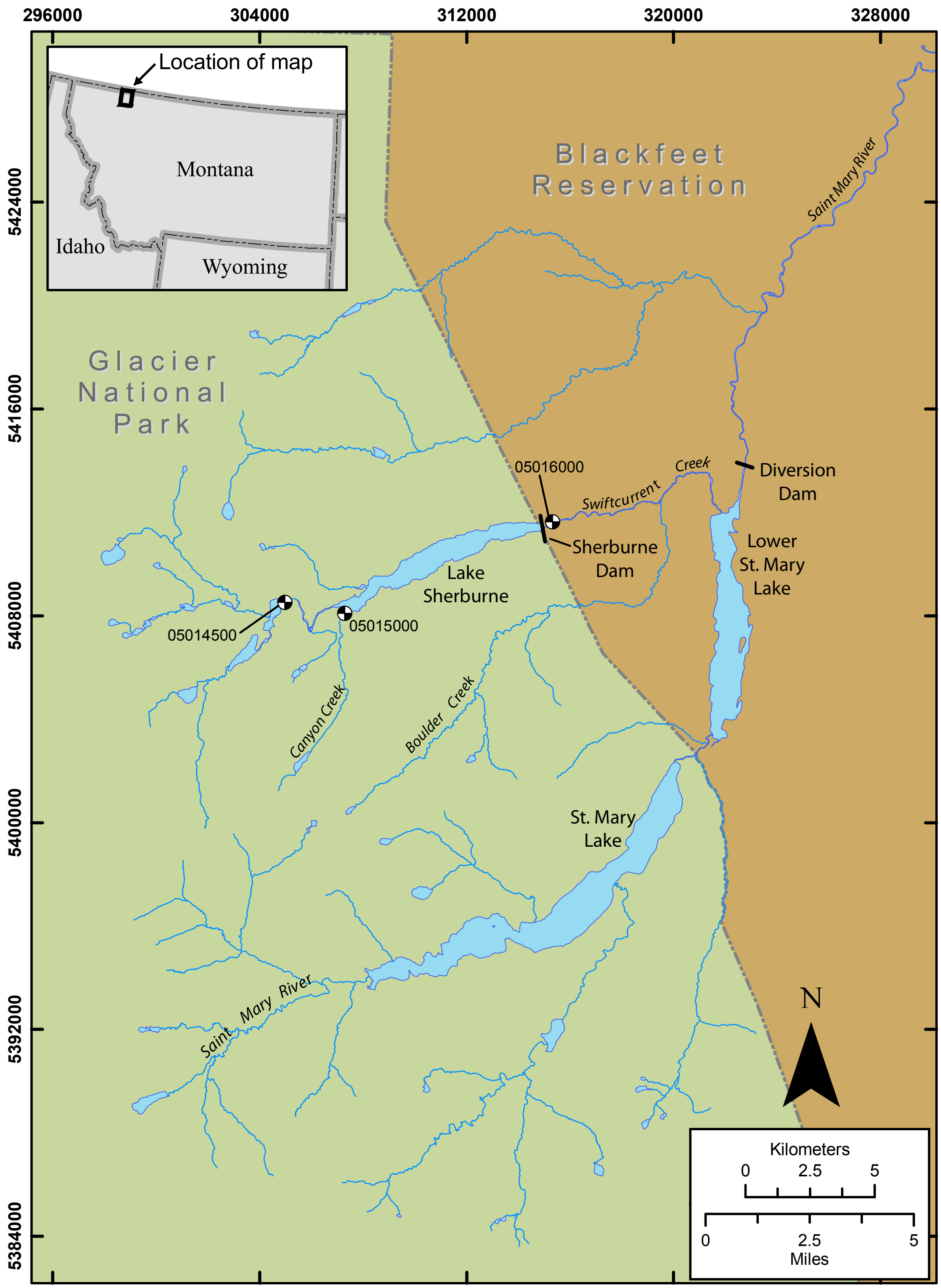

Figure 1. Location map. USGS gage locations are indicated by ◒ symbols and labeled with gage numbers. Study reach of Swiftcurrent Creek is from Sherburne Dam to confluence with Boulder Creek.

the larger Milk River Irrigation Project. Typical operations since around 1920 have consisted of water storage in the fall through spring, with closed outlet structure and minimal flow immediately downstream from the dam, followed by releases for downstream use during summer irrigation season. Several long-term streamflow gages provide data relevant to flow in the study reach (fig. 1, U.S. Geological Survey, 2008). Gage 05014500 (Swiftcurrent Creek at Many Glacier, MT) is upstream from Lake Sherburne and has been operated from 1912 to present (2008) with essentially year-round records since the late 1950s. This upstream gage provided the most extensive information on the seasonal pattern of natural streamflow in the study reach. Mean monthly discharges for calendar years 1959–2007 at the gage upstream from Lake Sherburne (fig. 2) were highest in May–July (490 ft^3/s in June) and lowest in December–March (26 ft^3/s in February). Gage 05016000 (Swiftcurrent Creek at Sherburne, MT) is immediately downstream from Sherburne Dam and was operated from 1912 through 2004, primarily as a seasonal gage. Gage 05015000 (Canyon Creek near Many Glacier, MT) was operated between 1918 and 1937 and provides data on a tributary to Lake Sherburne downstream from gage 05014500. We summarize some of the hydrologic records from these gages in the "Hydrology" section in order to register our results on fish passage geometry to natural winter streamflow in the study reach downstream from Sherburne Dam.

Methods

Our basic approach to defining the relationship between discharge and fish passage consisted of the following:

- Select a set of specific locations ("bottleneck" cross sections) representative of places in the study reach where fish passage was likely to be most quickly eliminated at lower discharges.
- Measure the bed topography at selected cross sections.
- Measure the water-surface elevations at selected cross sections during several specific Swiftcurrent Creek discharges produced by controlled settings of the Sherburne Dam outlet structure.
- Overlay the water-surface elevations on the bed topography to produce the cross-sectional area of water at different discharges and cross sections.
- Score each discharge and cross section according to the extent to which a cross-sectional area of water provided a minimum passage window of 15 by 45 cm.
- Summarize distribution of passability among "bottleneck" cross sections as a function of discharge.
- Examine sensitivity of relation between passability and discharge to assumptions about minimum passage window.

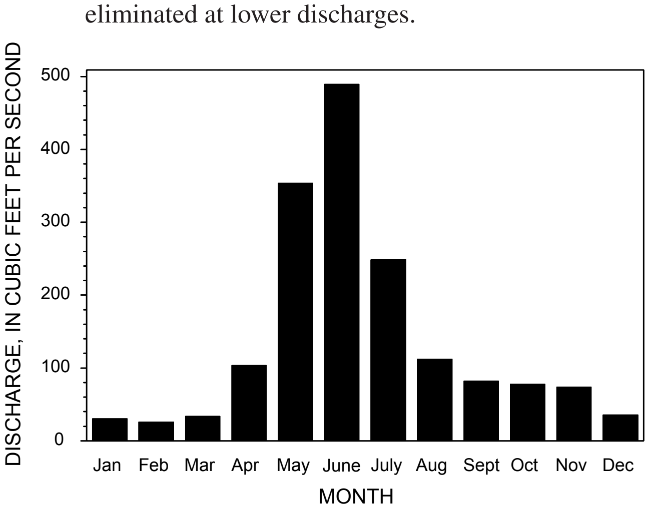

Figure 2. Mean monthly discharge at gage 05014500 (Swiftcurrent Creek at Many Glacier, MT) for calendar years 1959–2007.

In addition to the primary "bottleneck" cross sections previously described, we included four "pool" cross sections where adequate cross-sectional area of water likely existed at zero flow to avoid the impression that the "bottleneck" cross sections represented all of the geometry of Swiftcurrent Creek between Sherburne Dam and the confluence with Boulder Creek.

Field

We performed two basic types of field measurement: (a) stream discharge and (b) coordinate data for cross-sectional topography and water-surface elevations. Stream discharge was measured using a tag line and a SonTek FlowTracker Acoustic Doppler Velocimeter, primarily at one upstream and one downstream location (QA and QB in fig. 3). Vertical and horizontal coordinate data were acquired with survey-grade Global Positioning System (GPS) equipment and procedures. We used a combination of Trimble 4800, 5700/5800, and R8 GPS antenna receivers, Trimble TSC2 data loggers, and Trimble Survey Controller and Geomatics Office software. We measured in RTK (Real-Time Kinematic) survey mode from one base station (BASE in fig. 3) established on a permanent well casing. Coordinates were determined relative to NGS benchmark PID–AI7862 (National Geodetic Survey, 2007) on the outlet structure of Sherburne Dam (figs. 1 and 3). On several occasions, we set up a repeater station to facilitate work on the most distant cross sections. On two cross sections where canyon wall and satellite geometry were limiting, we used a Pentax PCS total station to obtain several topographic measurements in an integrated survey mode.

We selected "bottleneck" cross sections to represent locations where passage might be most limited at low discharge and also included several "pool" cross sections representing locations likely to have surface water at zero flow (fig. 4).

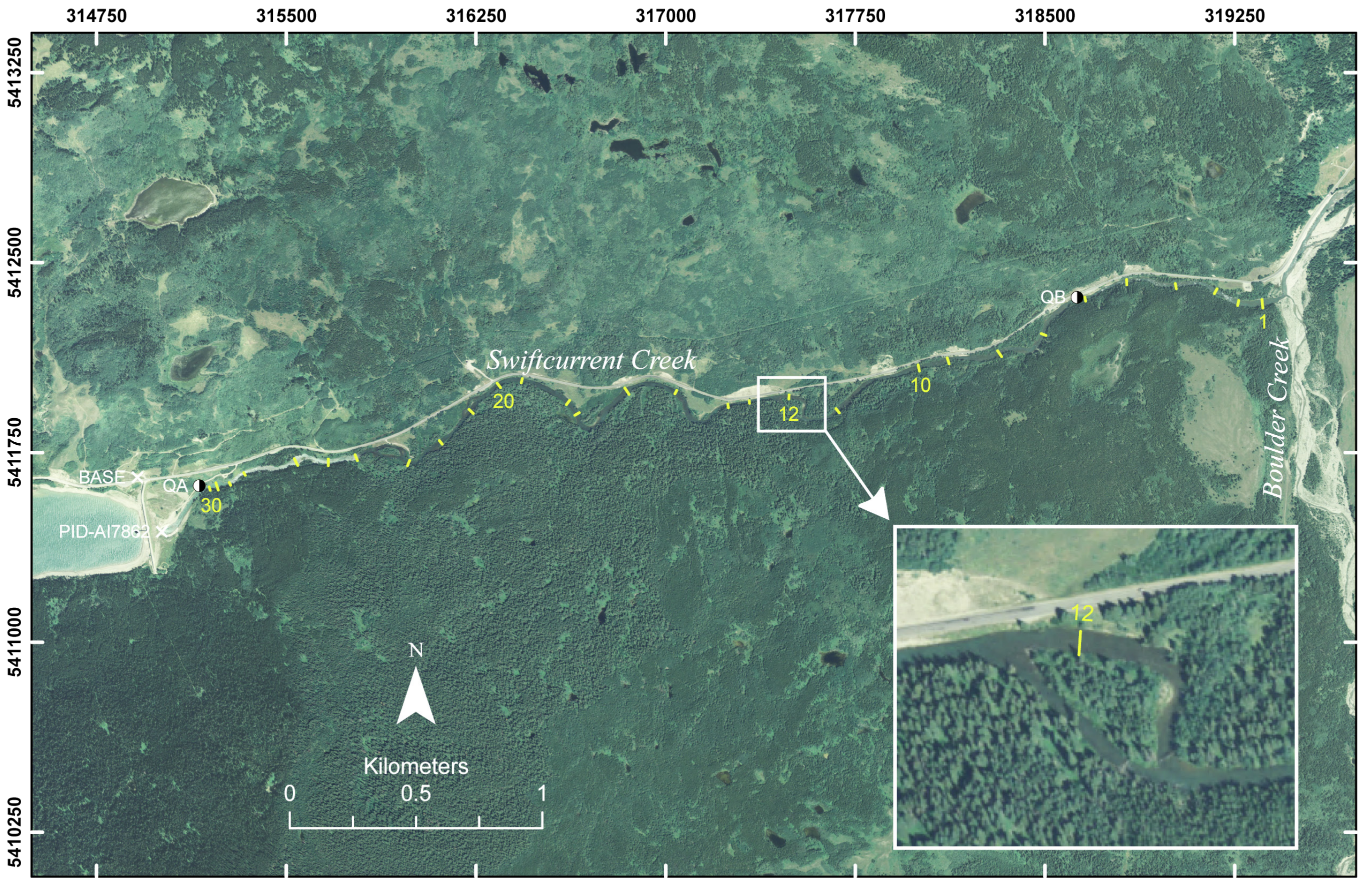

Figure 3. Locations of sampled cross sections along Swiftcurrent Creek. Locations of temporary discharge measurement sites (QA and QB) are indicated by ◑; and benchmarks indicated by X for National Geodetic Survey PID-AI7862 and temporary benchmark BASE. Area around cross section 12 is magnified to show relation to side channel.

We began by performing a longitudinal survey of thalweg elevations along what we judged to be the main channel during September 18–September 20, 2007. From this profile, we identified 26 general locations at or downstream from vertical control points as places where passage might be most limiting at low flow. We also identified general locations of four "pool" cross sections upstream from vertical control points on the longitudinal profile, where there was expected to be surface water at zero flow. Exact placement of "bottleneck" and "pool" cross sections at these general locations was then determined on the basis of visual examination of flow conditions at each location on the day that we surveyed cross-sectional bed topography. Cross sections are depicted by lines between their virtual (stored coordinates) head pins in figure 3. We surveyed channel topography during September 19–September 22, 2007, and June 2–June 7, 2008. Distances between virtual head pins ranged from 10.4 to 33.7 m, and cross sections had an average of 115 topographic points (range of 44 to 205).

We measured water-surface elevations at the cross sections at discharges associated with prescribed settings of Sherburne Dam outlet structure during September 11–September 13, 2008. We attempted measurements at five settings for the Sherburne Dam outlet structure but had to discard data from one release setting because of aberrant, and not reliably correctable, measurements most likely caused by a slipped rod height setting. This resulted in water-surface elevations at discharges of 1.2, 12.7, 24, and 31.5 ft^3/s. Based on previous examination of changes in water-surface elevations near the downstream end of the study reach in response to a changed release from Sherburne Dam, we estimated that flow stabilized throughout the study reach in less than 3 hours. We allowed at least 3–4 hours for stabilization following a change in the settings on the Sherburne Dam outlet control structure and then measured discharge at locations near the upper and lower ends of the study reach release (QA and QB in fig. 3). Water-surface elevations were measured in a stake-out-to-line mode from stored coordinates for the virtual head pins on each cross section. Using multiple rovers, we were able to complete a set of water-surface elevation measurements at all cross sections in less than 3 hours. At each discharge, at least one to as many as seven water-surface elevations were measured along each cross section on the basis of visual evaluation of horizontal variation in water surface.

We first attempted measurement of water surfaces at fixed, low discharges during June 2–June 7, 2008, because experimental operations of Sherburne Dam were easily

Figure 4. Examples of passage-limiting or “bottleneck” (top four panels) and “pool” (bottom two panels) locations along study reach of Swiftcurrent Creek.

implemented during this period. Runoff entering the study reach from snowmelt and rain during this time produced variable and substantial (relative to the low releases from Sherburne Dam) increases in discharge from the top to the bottom of the study reach. During this period, high runoff in Boulder Creek (relative to the low flows in Swiftcurrent Creek produced by low discharges from Sherburne Dam) also produced backwater effects elevating water surfaces at the two most downstream cross sections along Swiftcurrent Creek. We identified 13 major and 21 minor point sources of ephemeral tributary input (fig. 5) and explored combining multiple discharge-measurement locations with a regression model to estimate the discharge at each individual cross section. However, the amount of ephemeral accretion was large and variable relative to the Sherburne Dam releases of interest: 39 to 55 ft^3/s from station QA to QB in figure 3 on June 2, 2008; 14.5 to 25 ft^3/s on June 3; 1.6 to 8.8 ft^3/s on June 6; and 25 to 32 ft^3/s on June 7. Combined with the complexity of interpolating and interpreting data from a different set of discharges on each cross section, these considerations led us to abandon this approach in favor of subsequent measurements in late summer under drier conditions when there was no significant surface inflow along the study reach.

Analysis

We used a combination of Trimble Geomatics Office Ver. 1.63, MS Excel 2003, ArcGIS Ver. 9, and SAS Ver. 9.1 for data processing and analysis. First, we rotated and translated cross-sectional topography and water-surface elevation coordinate data to a common cross-sectional frame of distance along the cross section and height relative to the channel

Figure 5. Examples of ephemeral inflows to Swiftcurrent Creek.

thalweg. We then created piecewise linear polylines for the water surface at each discharge and cross section over the full topography of each cross section. This involved creating additional water-surface points to extend flat water surfaces measured with a single point or measured within the channel, and connecting multiple measurement points on a water surface that was irregular at a given discharge. In general, created points merely extended flat surfaces of the measured points. There were two exceptions where straight-line extensions of measured water surfaces strongly overestimated the water surface in an unmeasured, isolated part of the channel at a given discharge. These two cases were corrected by adding water-surface points in the unmeasured section that were the same as water surfaces in those locations at the next highest discharge.

We then used polylines representing channel topography at cross sections in combination with the polylines representing the water surfaces at different discharges at the respective cross sections to determine cross-sectional areas associated with each discharge. The evaluation of how much of these areas satisfied minimum passage criteria involved several steps of spatial analysis. For a given discharge and cross section, we first created a new polyline ("drop" line) by shifting the water-surface line down a distance, H, equal to the minimum passage height (15 cm). We then performed an intersection of this "drop" line with the line representing channel topography and removed those segments where the channel topography was higher than the "drop" line. This resulted in a set of line segments where points H distance below the water surface were above the bottom of the channel. We then determined the horizontal length of these segments and eliminated all of them whose horizontal length was less than the minimum passage width, W (45 cm).

The resulting set of lengths represented parts of the cross section that satisfied the minimum passage criteria of at least H distance of depth (15 cm) occurring in a contiguous width of at least W (45 cm). This set of lengths could be empty if no part of the cross section met the minimum passage criteria. This could happen if the water was shallower than H over an entire cross section. It could also happen in places where the water was deep enough (greater than H), all of which occurred in sections that were too narrow (lengths less than W). The set of lengths could contain only a single segment if the water was deeper than H in the middle of the cross section and became shallower only at the banks. The set of lengths could also contain multiple segments if the channel topography was irregular with multiple deep (at least H) sections with lengths of at least W, separated by shallower sections. In order to obtain an overall measure of how well a given discharge and cross section satisfied the criteria, we summed the channel lengths meeting the minimum passage criteria for the respective discharge and cross section. A semiautomated implementation of these steps allowed us to repeat the steps on multiple cross sections and discharges and to conduct sensitivity analysis of the minimum passage criteria by varying H and W.

Hydrology

The distribution of daily discharge under natural streamflow at the study reach during winter low-flow periods would be useful in assessing fish passage under natural conditions. Unfortunately, this information is not directly available. The gage in the study reach (gage 05016000, Swiftcurrent Creek at Sherburne, MT) was generally only operated seasonally and has little record that was not significantly affected by dam operations. Gage 05014500 (Swiftcurrent Creek at Many Glacier, MT) has a long, year-round period of record but is somewhat upstream from the study reach (fig. 1). Nonetheless, this upstream gage can provide a minimum estimate of the distribution of daily natural streamflow at the study reach. Figure 6 portrays the minimum, median, and maximum values of daily discharge at gage 05014500 (Swiftcurrent Creek at Many Glacier, MT) within each month in the low flow period of October–April when natural streamflow is low, and when closure of Sherburne Dam has typically further reduced downstream flows to near zero values. In every year from 1959 to 2007, all of these months had at least one daily flow greater than 9 ft^3/s (lowest of 9.7 ft^3/s for February in distribution of maximum daily flows, fig. 6). Median daily flows within each month were also lowest in February with 50 percent of years having values below 21 ft^3/s (distribution of median daily flows, fig. 6). Individual daily flows were less than 5 ft^3/s in only two of the months from 1959 to 2007: four days of zero flow in November 1976, and four days of 4.0–4.5 ft^3/s in February 1985 (distribution of minimum daily flows, fig. 6).

Gage 05014500 (Swiftcurrent Creek at Many Glacier, MT) upstream from the study reach has a contributing drainage area of 80 km^2, whereas the contributing drainage area at the study reach is approximately twice as large—166 km^2 at the dam itself and 167 km^2 at gage 05016000 at the upper end of the study reach shortly downstream from the dam (U.S. Geological Survey, 2008). Thus, while gage 05014500 provides a reasonable estimate of the pattern of natural streamflow in the study reach, it underestimates natural streamflow magnitudes in the study reach.

We performed two calculations to assess how much gage 05014500 (Swiftcurrent Creek at Many Glacier, MT) upstream from Lake Sherburne might be underestimating natural flow magnitude at the study reach downstream from Sherburne Dam. The first was to compare the ratio of mean monthly discharge at the gage 05015000 on Canyon Creek (a tributary to Lake Sherburne downstream from gage 05014500) to mean monthly discharge at upstream gage 05014500. This comparison was limited to the months of June through September in the years 1921 through 1936 when complete daily records were available for both gages. Mean monthly discharges at the Canyon Creek gage were 17 percent of those at gage 05014500, whereas the contributing drainage area for the Canyon Creek gage is 23 percent of the drainage area of gage 05014500. We also compared estimated annual discharge at

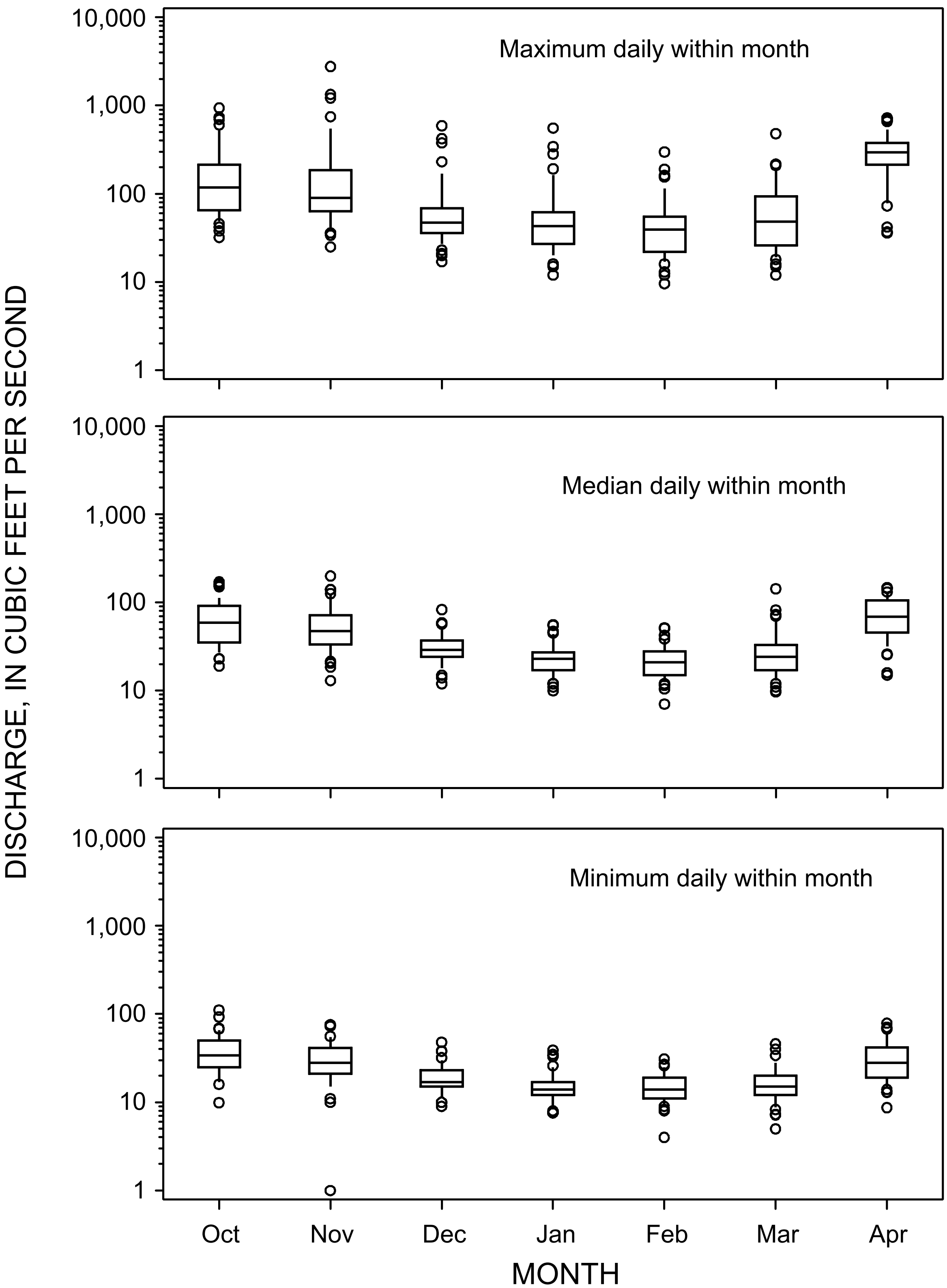

Figure 6. Distribution of minimum, median, and maximum daily discharge within months of October–April across calendar years 1959–2007 at gage 05014500 (Swiftcurrent Creek at Many Glacier, MT). Top and bottom of boxes are at 75th and 25th percentiles, whiskers extend to 90th and 10th percentiles, more extreme values are depicted by open circles.

seasonally operated gage 05016000 shortly downstream from Sherburne Dam (Swiftcurrent Creek at Sherburne, MT) to annual discharge at the upstream gage 05014500. We restricted this comparison to the 38 years between 1959 and 2004 when reasonable estimates of total annual discharge were available for both gages (complete daily records at 05014500, at least 200 days of record at seasonally operated 05016000, and first- and last-day seasonal values of measured or estimated discharge for 05016000 of less than 5 ft^3/s). Average values of the first and last days of recorded discharge at 05016000 for these 38 years were 0.7 and 0.4 ft^3/s, respectively. Estimated annual discharge at the study reach (gage 05016000) was 44 percent higher than the upstream gage 05014500 (Swiftcurrent Creek at Many Glacier, MT), whereas the contributing drainage area was 107 percent greater. There are many reasons for caution in interpreting these calculations, such as different elevational ranges of drainage areas and corresponding snowfall, differences in ratios between gages for overall as opposed to low-flow discharges, and likely underestimates of natural annual discharge at 05016000 due to unmeasured winter flow and reservoir evaporation. Nonetheless, measured discharge at gage 05014500 (Swiftcurrent Creek at Many Glacier, MT) and the distributions depicted in figures 2 and 6 clearly underestimate natural streamflow at the study reach, with natural streamflow at the top of the study reach (gage 05016000) perhaps on the order of 1.4 to 1.5 times streamflow at 05014500 (Swiftcurrent Creek at Many Glacier, MT).

Longitudinal and Cross-Sectional Geometry

We measured a longitudinal profile of the study reach of Swiftcurrent Creek from the confluence with Boulder Creek to shortly downstream from the outlet structure (figs. 1 and 3) to inform the selection of cross sections. This profile also allows a coarse estimation of pools or sections of the study reach with surface water at zero flow. Considering the resolution of the thalweg profile (66 points per kilometer), and using sections of the profile where upstream thalweg elevations were lower than a downstream thalweg elevation to define pools, resulted in 10 pool sections of the study reach that had a maximum depth of water of greater than 50 cm at zero flow. Total length of these deeper pool sections was approximately 25 percent of the total thalweg length, with a maximum individual pool length of 340 m. Maximum pool depth was 96 cm at zero flow from this calculation, although deeper locations clearly existed in some pools (fig. 7). The longitudinal profile also identified three sections (9 percent or 480 m of the main channel length) where well-developed side channels were present (fig. 3).

Experimental settings of the Sherburne Dam outlet structure during September 11–September 13, 2008, resulted in steamflow that was highly consistent along the study reach: 1.2 ft^3/s (0.7 at QA and 1.7 ft^3/s at QB); 12.7 ft^3/s (12.0 at QA and 13.3 ft^3/s at QB); 24 ft^3/s (24.2 at QA and 23.9 ft^3/s at QB); and 31.5 ft^3/s (31.1 at QA and 31.8 ft^3/s at QB). Water surfaces for these discharges and cross-sectional topography are illustrated in figures 7 and 8 for 4 of the 26 measured “bottleneck” cross sections and one of the “pool” cross sections (locations of cross sections indicated in fig. 3). Geographic coordinates of the virtual head pins and longitudinal profile points and the locations of channel-bed and water-surface points relative to the head pins are available as electronic data files at *http://pubs.er.usgs.gov/usgspubs/sir/sir20095100*.

Fish Passage

Using the minimum passage criteria of at least 15 cm of water depth in a contiguous section at least 45 cm wide, all of the four “pool” cross sections provided substantial passage geometry (greater than 5 m of total width) at the low discharge of 1.2 ft^3/s (fig. 9). Passage geometry at these “pool” cross sections increased very gradually with discharge from 1.2 to 31.5 ft^3/s.

In contrast, passage geometry at the 26 “bottleneck” cross sections increased strongly with discharge over the range of 1.2 to 24 ft^3/s (fig. 10). Most of the “bottleneck” cross sections did not satisfy the minimum (15 by 45 cm) passage criteria at 1.2 ft^3/s (median passable width of 0), and 25 percent of these cross sections had no passage at 12.7 ft^3/s. At 24 ft^3/s all but one of the “bottleneck” cross sections had some passage, and 90 percent had more than 3 m of width satisfying the minimum passage criteria. One of the cross sections (number 12) did not meet the 15 by 45 cm minimum criteria even at 31.5 ft^3/s (fig. 10). This cross section was in the main channel in a location where a side channel also was present (fig. 3). There was no flow in the side channel at 1.2 ft^3/s due to the bed topography upstream where the side channel separated from the main channel. However, as discharge increased, the side channel began to flow, producing relatively small increases in water surfaces at the main channel cross section, which was not receiving all of the increased discharge (cross section 12 in fig. 7).

Using a minimum passage window criterion of 15 by 45 cm and taking the 26 “bottleneck” cross sections as representative of passage-limiting locations in the study reach thus indicate (a) severe passage limitations at 1.2 ft^3/s, (b) substantially better but still substantially limited passage at 12.7 ft^3/s, and (c) generally good passage at 24 ft^3/s with the exception of a special-case location (fig. 10). Combining these results with estimates of natural streamflow in the study reach (figs. 2 and 6) further suggests that natural streamflow provided adequate passage at some times in most months and locations in the study reach, although not for all individual days and locations.

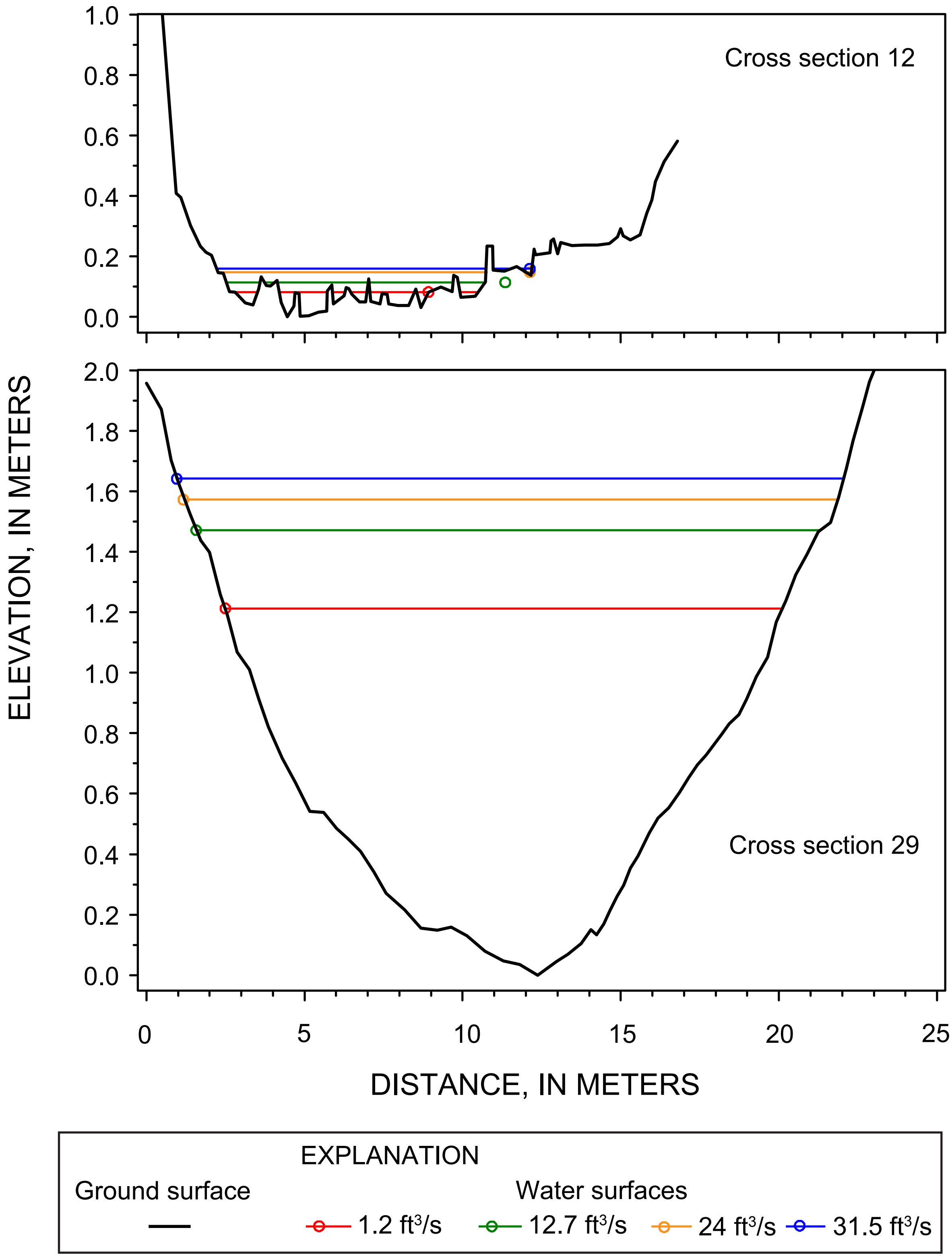

Figure 7. Topography and water surfaces at "bottleneck" cross section 12 and "pool" cross section 29. Circles depict water-surface measurement points. In cases where they appear as below the ground surface, the measurements were offset slightly from the cross section line to obtain a representative water surface with a stable rod placement.

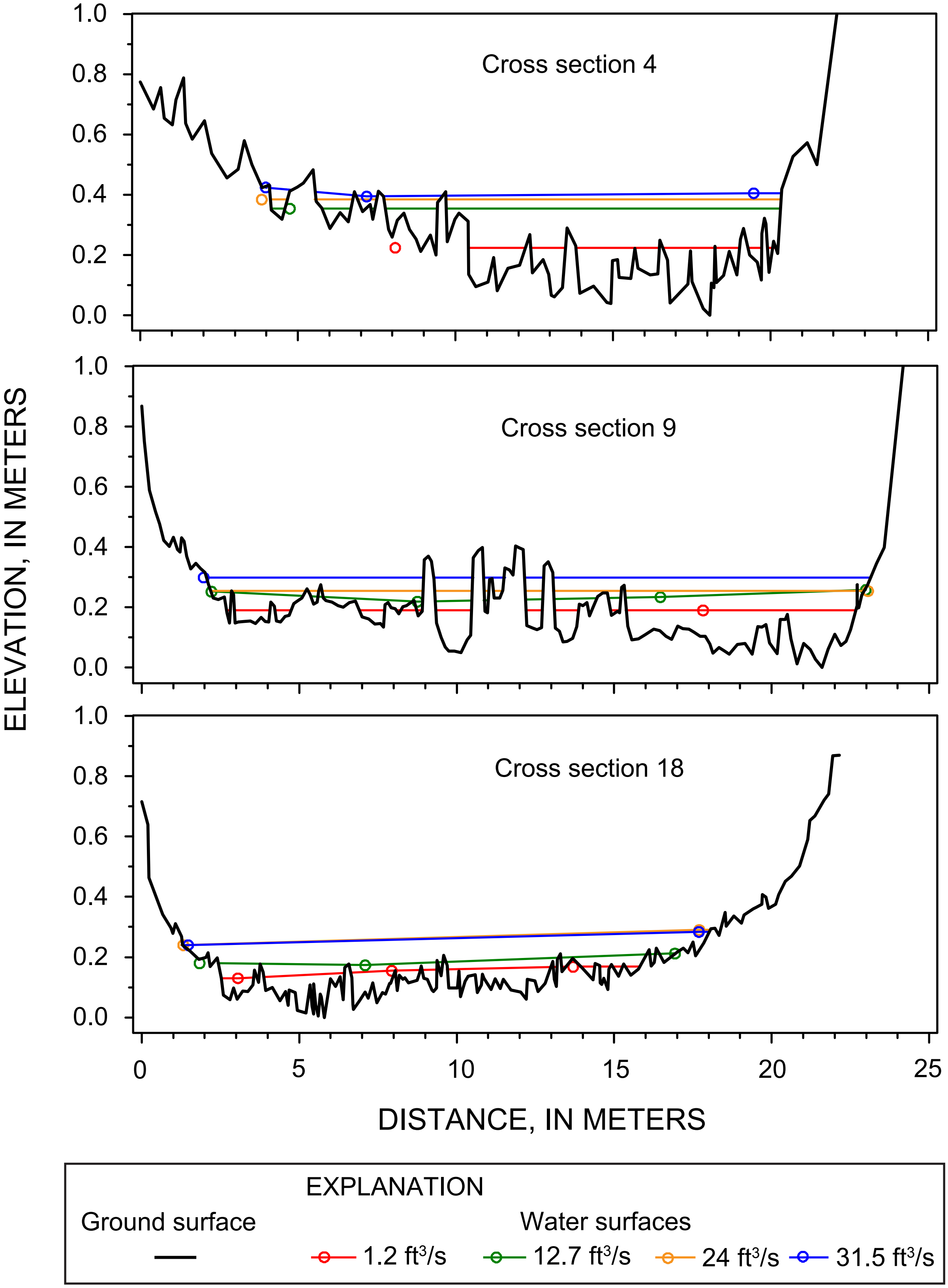

Figure 8. Topography and water surfaces at "bottleneck" cross sections 4, 9, and 18. Circles depict water-surface measurement points. In cases where they appear as below the ground surface, the measurements were offset slightly from the cross-section line to obtain a representative water surface with a stable rod placement.

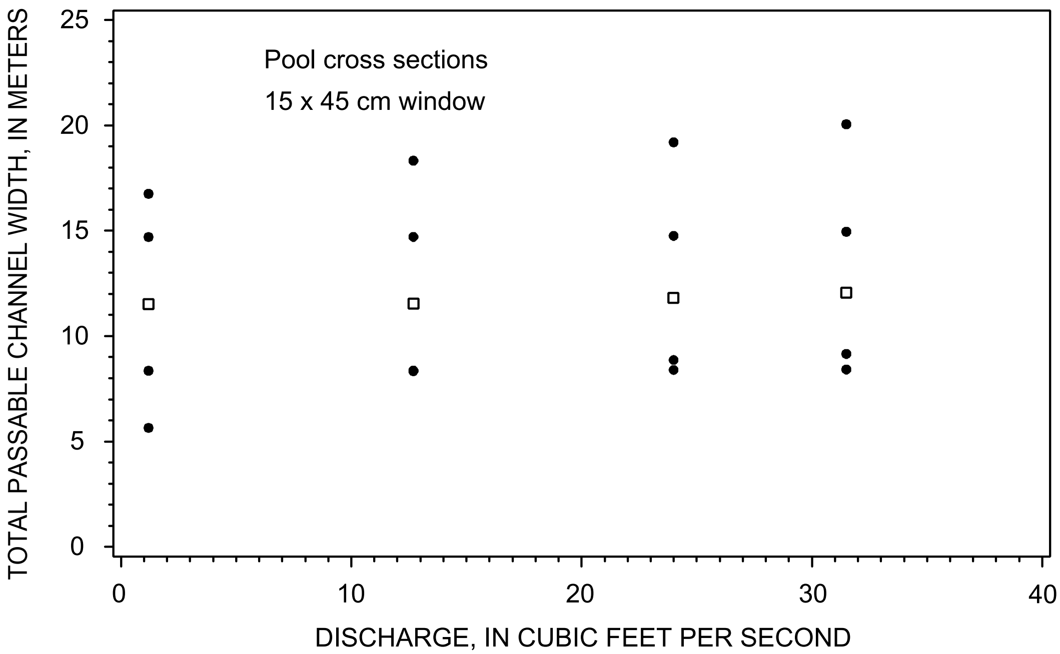

Figure 9. Total passable channel width at "pool" cross sections. Each of four "pool" cross sections is evaluated by total channel width that occurs in one or more passage windows with contiguous width of at least 45 centimeters with at least 15 centimeters of depth. Open square symbol is median at each discharge.

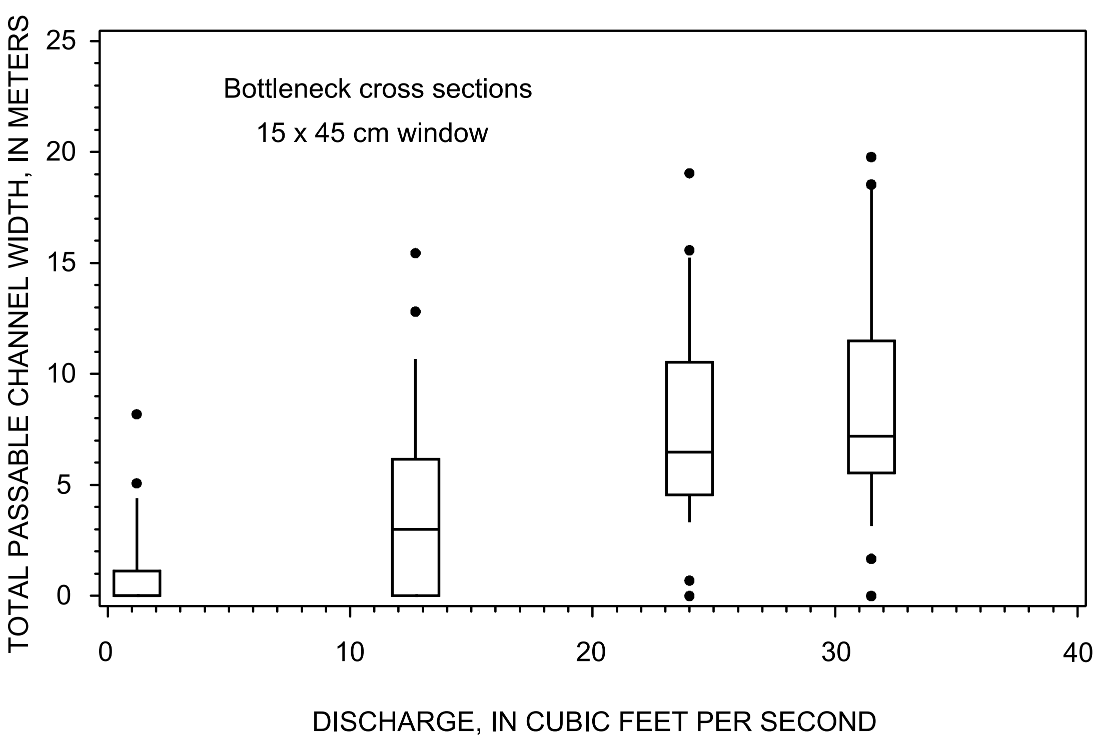

Figure 10. Total passable channel width at "bottleneck" cross sections. Each of 26 "bottleneck" cross sections is evaluated by total channel width that occurs in one or more passage windows with contiguous width of at least 45 centimeters with at least 15 centimeters of depth. Distributions of these total passable channel widths for the cross sections at different discharges are depicted by box plots (top and bottom of boxes are at 75th and 25th percentiles, whiskers extend to 90th and 10th percentiles, and more extreme values are depicted by solid circles).

Uncertainty

A number of limitations and uncertainties exist in both our analysis and in the relevance of that analysis to effects of Sherburne Dam releases on fish; these limitations need to be considered in any use or interpretation of the results presented here. These include assumptions about minimum passage geometry, measurement error, limitations of the cross-sectional model we used to characterize passage, the relation of Sherburne Dam releases to streamflow in the downstream study reach, and the relation of passage geometry, as we have measured it, to actual fish movement and potential stranding.

Minimum Passage Criteria

The definition of a minimum passage window as a polygon of at least 15 cm of water depth occurring in at least a 45-cm-wide contiguous section is based on multiple years of direct observation of streams in this area at times, conditions, and places where bull trout movements were known from electrofishing and radiotelemetry (for example, collection of field data described in Mogen and Kaeding, [2005a,b]). Nonetheless, these criteria for minimum passage geometry are best considered an assumption and are not likely to be a perfect or absolute threshold of whether bull trout can or cannot pass a given cross section. In order to examine the sensitivity of results to the minimum passage criteria, we replicated the analysis of passage at the 26 “bottleneck” cross sections under combinations of different assumed depths and widths of the minimum passage window. For this sensitivity analysis we summarize passability among the 26 “bottleneck” cross sections in terms of the 25th percentile of total passable width among the cross sections—the value of passable width that is exceeded on 75 percent of the “bottleneck” cross sections. Relations between discharge and passability for all combinations of 20- and 40-percent increases and decreases in both the depth and width of the minimum passage window (9, 12, **15**, 18, and 21 cm of depth and 27, 36, **45**, 54, and 63 cm of width) are depicted in figure 11. Increasing the dimensions of the minimum passage window makes the criteria more restrictive and generally decreases passability at a given discharge, whereas decreasing the minimum dimensions tends to increase passability at a given discharge. However, the overall pattern of strongly increasing passage from 1.2 to 24 ft^3/s is apparent on all combinations of dimensions of the minimum passage window. Increasing the minimum passage dimensions by 40 percent in both the depth and width (to 21 by 63 cm) still results in passage at 24 ft^3/s for the 25th percentile cross section. At 1.2 ft^3/s, only a 40-percent reduction in depth (to 9 cm) combined with a 20- or 40-percent reduction in width (to 36 or 27 cm) produces any passable width at the 25th percentile cross section. Overall, the passability of the 25th percentile cross section was more sensitive to minimum passage depth than minimum passage width. Decreasing the minimum depth by just 20 percent (to 12 cm) provided passage on the 25th percentile cross section for the nominal 45-cm width as well as for the increased minimum widths of 54 and 63 cm. In contrast, a 40-percent reduction in minimum passage width (to 27 cm) was required to provide passage on the 25th percentile cross section at the nominal passage depth of 15 cm.

Greater sensitivity to minimum passage depth was also evident in the exceptional cross section number 12 (fig. 7) that had no passage at the nominal passage window of 15 by 45 cm (fig. 10). At this cross section, a 20-percent decrease in minimum passage depth (to 12 by 45 from 15 by 45 cm) produced passage at 24 ft^3/s, whereas a 20-percent reduction in minimum passage width (to 15 by 36 cm from 15 by 45 cm) produced passage only at the higher discharge of 31.5 ft^3/s.

In summary, the sensitivity analysis suggests that the overall results are not highly dependent on exact dimensions of the minimum passage window. Around nominal dimensions of 15-cm depth by 45-cm width, (a) passage is somewhat more sensitive to minimum depth than minimum width, (b) substantial (40 percent) increases in the dimensions of the minimum passage window still result in widespread (25th percentile of “bottleneck” cross sections) passage at 24 ft^3/s, and (c) substantial decreases in minimum passage dimensions (20 or 40 percent of depth or 40 percent of width) might move the discharge required to provide widespread passage (25th percentile of “bottleneck” cross sections) down from somewhere between 12.7 to 24 ft^3/s to a value somewhat below 12.7 ft^3/s.

Measurement Error

The empirical relation between streamflow and passage geometry depends on quantifying discharge at the cross sections and measuring coordinates of bed topography and water surfaces at the cross sections. We abandoned or discarded measurement attempts where we suspected any systematic error or bias—variable discharge produced by flowing ephemeral sources during June 2–June 7, 2008, and a set of water-surface elevations in which some cross sections had aberrant (slipped rod) antenna heights. Some measurement error nonetheless remains. In three cases, we replicated a stream discharge measurement by making a second measurement at the same location. The average difference between subsequent measurements was 0.75 ft^3/s with a maximum difference of 1.6 ft^3/s (55.75 and 55.35 ft^3/s). Our analysis assigns a single discharge to the entire set of cross sections measured during a 3-hour period of steady flow with no visible inflows along the study reach. We measured discharge at locations near the top and bottom of the study reach (QA and QB in fig. 3) during each period of water-surface measurement and used the mean of the two values. Discharge at the two locations differed by an average of 0.8 ft^3/s (maximum difference of 1.3 ft^3/s) and was not consistently higher at the downstream station.

Coordinate error in cross-sectional geometry and water surfaces stems from both instrument error and from judgments about placement and density of individual points that represent the surfaces as a piecewise linear polyline. We registered

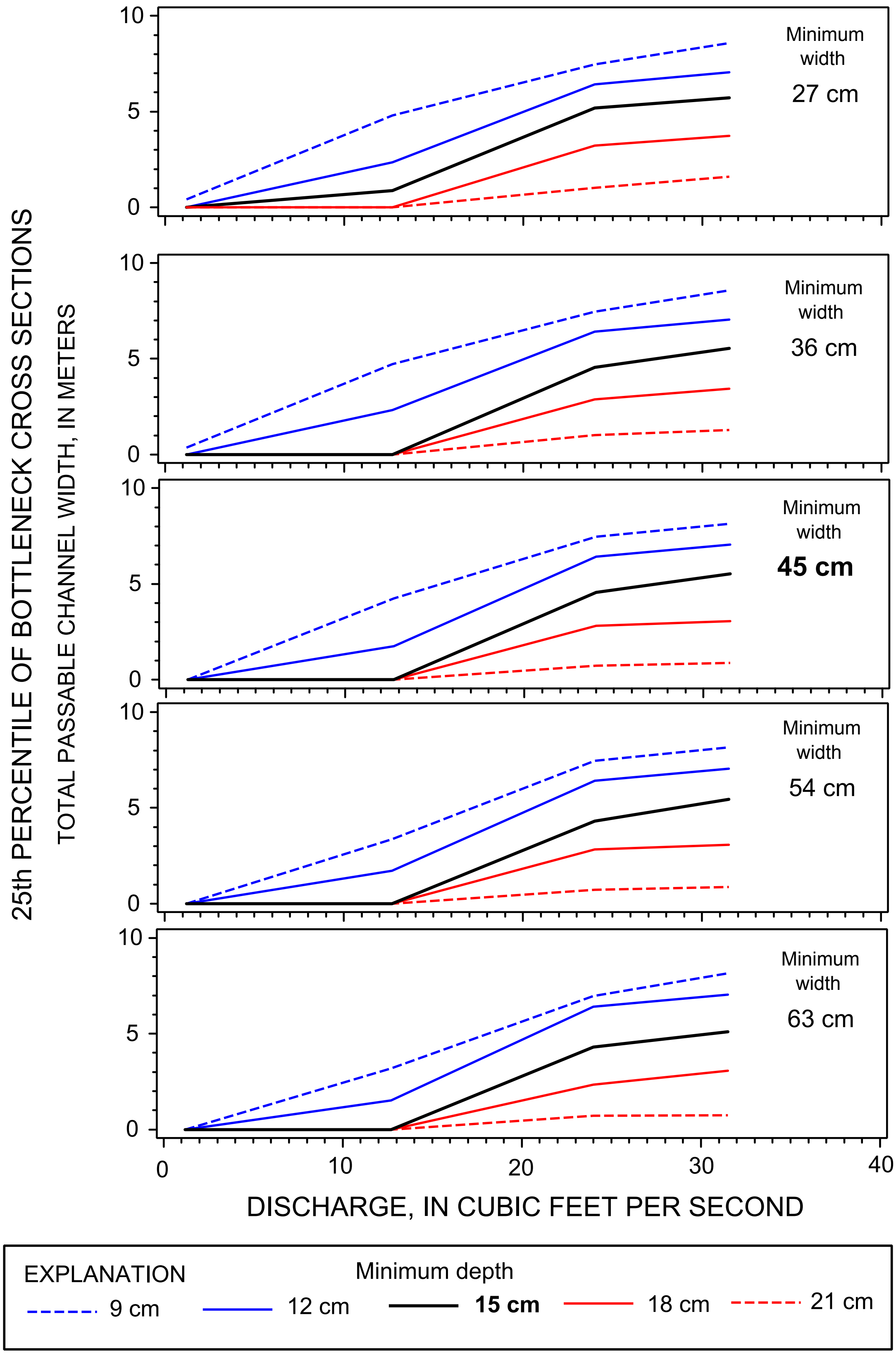

Figure 11. Sensitivity of total passable channel width to changes in threshold depth and width of minimum passage window. Values are the 25th percentile of the "bottleneck" cross sections at each discharge, varying the minimum threshold depths and widths by 20 and 40 percent around the nominal passage window of 15 by 45 centimeters.

all coordinate data from NGS benchmark PID AI7862 on the Sherbune Dam outlet structure (fig. 3). As part of the survey, we also measured NGS benchmark PID AI7863 on the St. Mary River diversion dam (fig. 1) and obtained vertical and horizontal coordinates that differed by less than 1 cm from published values (National Geodetic Survey, 2007). As a part of a long-term effort to assess the precision of our use of survey-grade GPS equipment for riverine work (T. Waddle, unpub. data, 2008), the same equipment and procedures (RTK mode from base) have been used to resurvey a fixed point in a canyon environment (Cache la Poudre River in northern Colorado). Randomly selecting a single RTK observation from each of seven separate base setups over a 4-year period produces an estimate of deviations from the centroid location that might be expected using the Swiftcurrent Creek field procedures and equipment. Median absolute vertical deviation from this data set was 1.2 cm (maximum of 2.9 cm) and median absolute horizontal (hypotenuse of northing and easting dimensions) deviation was 0.9 cm (maximum of 2.8 cm). The adequacy of survey point location and density in representing a complex surface is somewhat more difficult to assess because it depends on knowing the true surface (which is not known beyond how it is represented by the points observed). Field judgments on point locations and densities were guided by what was needed to determine whether a 15 by 45 cm passage window would or would not exist at different water surfaces. Cross-sectional topographic measurements were relatively dense and had an average of five points per meter of cross section.

The approximate precision of individual measurements is ±1 cm with a maximum deviation of 3 cm. This magnitude of elevational difference can change the passage provided at specific discharges in particular locations considering the patterns depicted in figures 7, 8, 10, and 11. However, there is no reason to suspect systematic over- or under-representation of passage provided at a given discharge. Thus, it is most reliable to focus interpretation on a general empirical relation between the distribution of passage geometry among multiple cross sections with increasing discharge, rather than the precise geometry at one location and one discharge.

Limitations of Cross-Sectional Model

Our approach evaluates passage geometry in terms of the minimum areas under the water surface at cross sections. Furthermore, we summarize overall passage by treating cross sections as if they were independently responding to discharge. While not wrong in itself, this approach can miss higher-dimensioned patterns that emerge from longitudinal (upstream-downstream) channel topography or the arrangement of cross sections. Some of those effects are evident in the variation of our measured responses of the increase in water-surface elevations and passage with increasing discharge on individual cross sections. Examples include (a) the differences between “pool” and “bottleneck” cross sections (figs. 9 and 10) due to the geometry of downstream controls; (b) limited increases in passage with discharge at cross section 12 as upstream channel geometry causes water to be diverted into a parallel side channel; and (c) back-water effects at the most downstream cross sections observed in June 2–June 7, 2008, when flow in Boulder Creek was substantially higher than flow in Swiftcurrent Creek.

Another limitation of our cross-sectional view of passage comes from situations where the longitudinal channel geometry produces adequate passage on all the cross sections in a longitudinal segment of river, but where there is still no path of adequate passage from the upstream to downstream ends of the section. We observed at least one place where this might be occurring at which a long (2 to 3 times channel width) cross-channel bar produced deep areas of flow on upstream, river-left cross sections, deep flow on downstream, river-right cross sections, but only very shallow flow over the top of the bar feature and thus no deep flow path from one side to the other side of the river. An alternative analysis approach might consider the full 3-dimensional bed topography of the study reach with 2-dimensional hydraulic models to determine water-surface elevations and then quantify the size and existence of continuous passage lines from the upstream to downstream ends of the study reach. This would likely be required to determine the exact location of passage limitations at a given flow. On the other hand, this approach would require substantially more data-collection and analysis effort. It seems difficult to justify 2-dimensional modeling in order to determine a general idea of what discharges are likely to limit passage geometry given uncertainties about exact fish passage requirements, fish behavior, and the stability of channel-bed geometry over time.

Relation to Sherburne Dam Releases

Accretions from ephemeral point sources such as we observed in June 2–June 7, 2008, can produce substantially higher discharges, water surfaces, and passage at downstream locations in the study reach than would be associated with a low-flow release from Sherburne Dam. The accretions during June 2–June 7, 2008, when snowmelt runoff was being combined with rainfall, were atypical of late summer, fall, and winter conditions during which accretions are typically small. Nonetheless, our results on the relation between passage and discharge (fig. 10) should be viewed as a bounding case reflecting the situation in which accretions are minimal and the outflow from Sherburne Dam provides essentially all the flow throughout the study reach.

Relation to Fish Response

Our results are limited to the physical geometry of passage in relation to streamflow in the absence of ice cover. Fish will be trapped in pool locations in the absence of adequate passage geometry. Furthermore, the presence of ice cover is more likely than not to further limit the physical passage available at a given discharge. Adequate passage geometry, however, does not guarantee that fish will move out of pools, nor does it address whether fish will or will not survive in pool locations at different water depths, ice thicknesses, flow rates, oxygen levels, or predation pressures.

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Sue Camp of the Bureau of Reclamation led the scoping of this study and provided essential direction, coordination, and field assistance during its implementation. Steve Germaine and Elizabeth Reynolds assisted with field data collection. Tammy Fancher and Colin Talbert assisted with elements of the data analysis and graphics.

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