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[Article]

Effectiveness of a Redesigned Water Diversion Using Rock Vortex Weirs to Enhance Longitudinal Connectivity for Small Salmonids

KYLE D. MARTENS* AND PATRICK J. CONNOLLY

U.S. Geological Survey, Western Fisheries Research Center, Columbia River Research Laboratory, 5501A Cook-Underwood Road, Cook, Washington 98605, USA

Abstract.—For nearly 100 years, water diversions have affected fish passage in Beaver Creek, a tributary of the lower Methow River in north-central Washington State. From 2000 to 2004, four dam-style water diversions were replaced with a series of rock vortex weirs (RVWs). The weirs were designed to allow fish passage while maintaining the ability to divert water into irrigation canals. We observed the new appearance of three species (juvenile Chinook salmon *Oncorhynchus tshawytscha*, juvenile coho salmon *O. kisutch*, and mountain whitefish *Prosopium williamsoni*) upstream of the RVWs, indicating successful restoration of longitudinal connectivity. We used passive integrated transponder (PIT) tags and instream PIT tag interrogation systems during 2004–2007 to evaluate upstream passage of small salmonids (<240 mm fork length) through one series of RVWs. We documented 109 upstream passage events by small salmonids through the series of RVWs; most of the events (81%) involved passage of rainbow trout *O. mykiss* or juvenile steelhead (anadromous rainbow trout). Small rainbow trout or steelhead ranging from 86 to 238 mm (adjusted fork length) were able to pass upstream through the RVWs, although a delay in fish passage at discharges below 0.32 m^3/s was detected in comparison with nearby control sections.

The use of water diversions to irrigate crops and raise livestock continues to be a common practice for farmers and ranchers in the western United States. However, some of these diversions can act as barriers that limit the movement, distribution, and abundance of fish within and between watersheds (Bednarek 2001; Connolly and Sauter 2008). The diversions can also affect the composition of fish communities (Bednarek 2001) and reduce genetic variability of fish populations (Neville et al. 2006). The most recognized impact of instream barriers on fish movement in the Pacific Northwest is the blockage of adult salmonid access to historical spawning areas. However, even when adults can pass upstream, these structures can severely restrict upstream passage of juvenile salmonids (Curry et al. 1997; Erkinaro et al. 1998). This restriction can limit or block access to critical rearing areas (Scrivener et al. 1993), access to refugia from predation (Harvey 1991), and colonization of fish populations after disturbances (Detenbeck et al. 1992). Habitat fragmentation resulting from blocked passage can increase risk of extirpation of fish populations (Winston et al. 1991).

Direction and timing of fish movement can be difficult to assess by use of most common tagging methods (Bunt et al. 1999). Ficke and Myrick (2009) noted the limited number of techniques for effectively monitoring small-bodied fish in natural stream conditions. Typical tagging methods, such as Floy tags (Belford and Gould 1989), visible implant elastomer tags (Schmetterling et al. 2002; Ficke and Myrick 2009), acrylic paint injection (Warren and Pardew 1998), and radiotelemetry (Bunt et al. 1999; Ovidio and Philippart 2002), have serious limitations for determining fish direction and timing. Floy tags, visible implant elastomer tags, and acrylic injection techniques cannot provide information regarding specific travel times through a section of stream unless traps are continuously operated upstream and downstream of a specific section of interest. The use of radiotelemetry can provide travel time data; however, the number and size of tagged fish can be limited due to the size, cost, and life span of the tags. Passive integrated transponder (PIT) tags and fixed instream interrogation systems can be used to determine the direction and exact time of fish movement (Connolly et al. 2008), to relate the time of movement to near-instantaneous streamflow conditions (Bryant et al. 2009), and to tag large numbers of fish for a relatively low cost. For these reasons, the use of PIT tags has shown much potential for studies of fish movement.

Passive integrated transponder tags and instream interrogation systems have been successfully used to study large (>250 mm) migratory fish at natural-style passage structures (Aarestrup et al. 2003; Calles and Greenberg 2007), but few studies have examined small fish, which may or may not have migratory tendencies. Fish passage through rock vortex weirs (RVWs; Figure 1) has received little attention in laboratory and field studies (Ruttenberg 2007). Structures such as RVWs

* Corresponding author: kmartens@usgs.gov

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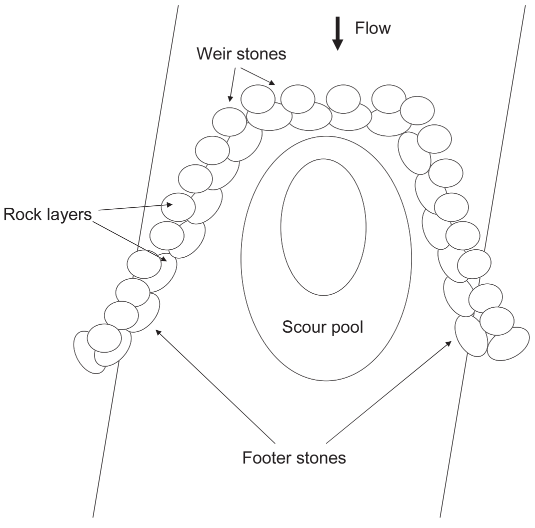

FIGURE 1.—Design of a typical rock vortex weir.

are built in a "close-to-natural" style that resembles natural river rapids (FAO/DVWK 2002). These types of structures offer an alternative to more traditional passage structures and can potentially create a more aesthetic look to the landscape (Jungwirth 1996). Some advantages of these natural-style structures include the variety of flows and depths for movement of different fish species and sizes and the creation of habitat (Aarestrup et al. 2003). Previous evaluations of natural-style structures have revealed mixed results (Aarestrup et al. 2003; Calles and Greenberg 2005, 2007), creating the need for more informative studies (Roni et al. 2002). Before the role of RVWs for instream restoration increases, their effectiveness should be assessed to justify large expenditures and to prevent the replication of flawed designs. The objectives of this study were to (1) assess the effectiveness of a series of RVWs in permitting upstream passage of small fish and (2) assess the effects of stream discharge and fish length on speed and timing of fish movement through the series of RVWs.

Study Area

Our study was conducted in Beaver Creek, a tributary of the lower Methow River in north-central Washington State (Figure 2). The Methow River is a fifth-order stream that drains into the Columbia River at river kilometer (rkm) 843. Beaver Creek is a third-order stream that drains westward into the Methow River at rkm 57 just south of Twisp, Washington. The watershed has an area of 179 km^2 (USFS 2004) and ranges in elevation from 463 to 1,890 m. Discharge in Beaver Creek is typically highest in May and June and then declines to base levels during August–October. From July 2004 to September 2007, the lowest daily median discharge was 0.05 m^3/s (September 2005), and the highest daily median discharge was 4.70 m^3/s (May 2006; Ruttenberg 2007).

Prior to restoration, various artificial and natural barriers existed in the Beaver Creek watershed for more than 100 years. One of these barriers was a small, concrete dam, while the other diversion barriers were structures made from a mixture of materials, such as wood, rocks, and plastic sheeting. The concrete diversion dam was modified in 2004, whereas three other upstream diversion dams were modified in 2003. At least two of these diversions were considered barriers to upstream fish passage before installation of the RVWs (USBOR 2004a, 2005). The RVWs in Beaver Creek were designed and installed under the supervision of the U.S. Bureau of Reclamation to meet fish passage standards established by the National Marine Fisheries Service (NMFS 2000) and the Washington Department of Fish and Wildlife (WDFW 2000).

Modifications to the water diversions in Beaver Creek included the installation of a series of RVWs at a given site (USBOR 2004a, 2004b, 2004c, 2005). These RVWs were made of large boulders to increase the stream elevation so that it matched the height of the original diversion. A typical RVW was pointed upstream with the "legs" angling downstream from 15° to 30° relative to the streambank (Figure 1). Footer stones were installed along rock layers, and weir stones were positioned above them. Rock vortex weirs were designed to allow passage of water and biota around and between the rocks at normal flows, creating a variety of flow velocities and depths to accommodate fish passage (SMRC 2008). The RVWs typically create scour pools downstream of the weirs, which have the potential to provide rearing habitat and a jump pool for fish. Although RVWs are not new (Roni et al. 2002), their effectiveness for allowing upstream passage of small fish is largely unknown and is likely to vary among sites.

Before the construction of the Lower Stokes Water Diversion (LSW) on Beaver Creek, rainbow trout *Oncorhynchus mykiss*, steelhead (anadromous rainbow trout), brook trout *Salvelinus fontinalis*, and shorthead sculpin *Cottus confusus* could be found just upstream of the LSW area. Downstream of the LSW, anadromous salmonids (primarily steelhead but also Chinook salmon *O. tshawytscha* and coho salmon *O. kisutch*), nonanadromous salmonids (rainbow trout, westslope cutthroat trout *O. clarkii lewisi*, bull trout *Salvelinus confluentus*, mountain whitefish *Prosopium williamsoni*, and brook trout), and nonsalmonids (shorthead sculpin, longnose dace *Rhinichthys cataractae*, bridge-

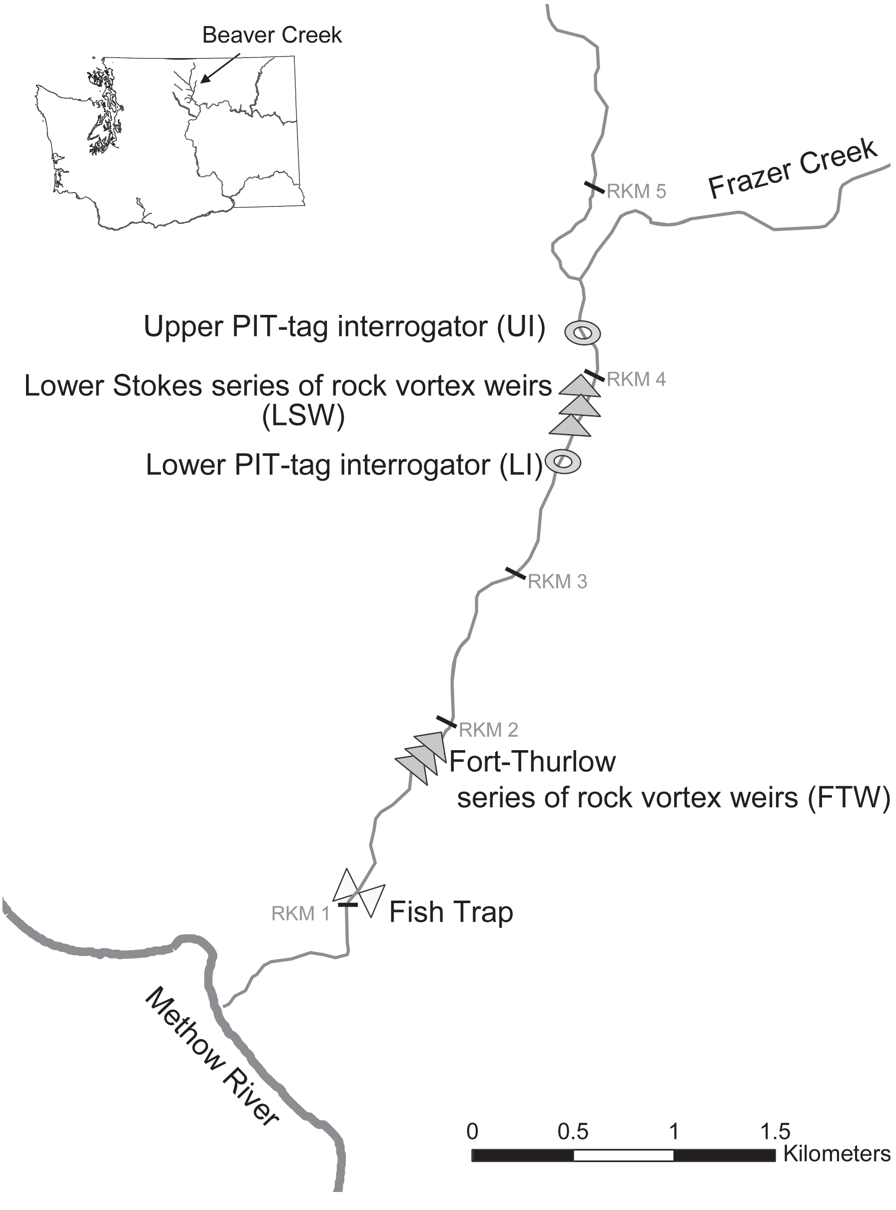

FIGURE 2.—Sites for locations of passive integrated transponder (PIT) tag interrogators, the fish trap, and the series of rock vortex weirs in Beaver Creek, Washington (RKM = river kilometer). The upper interrogator (UI) was a multiplexing system with six antennas, while the lower interrogator (LI) was a single-antenna system.

lip sucker *Catostomus columbianus*, and smallmouth bass *Micropterus dolomieu*) were present (Martens and Connolly 2008).

Methods

Fish were collected by use of a two-way fish trap at Beaver Creek (rkm 1; Figure 2) and backpack electrofishers. To track fish movements, a 12.5-mm PIT tag (full duplex, 134.2 kHz) was applied to most fish of 65 mm or greater lengths. Electrofishing was conducted at the lower sampling area (rkm 1), upstream and downstream of the LSW, and in the upper watershed. We intensively sampled a 600-m section of stream immediately upstream of the LSW multiple times during each year of the study (2004–2007) to PIT-tag fish, recapture previously PIT-tagged fish, and look for the presence of new species above the LSW. Surveys were conducted in the spring, summer, and fall.

A fish trap was deployed at rkm 1 and was used to collect and tag upstream-moving fish below the LSW. The two-way fish trap was operated during 22 October–22 December 2004 (60 d); 20 March–5 December 2005 (253 d); 13 February–27 April and 28 June–27 November 2006 (220 d); and 24 February–30 March and 25 May–30 September 2007 (219 d). The trap was checked a minimum of once per day. Trap operations were typically compromised by high flows during the fall and early spring. The trap was removed during winter due to ice accumulations. Fish trapping operations started in late-fall 2004 and extended through fall 2007.

We maintained and operated one multi-antenna, multiplexing PIT tag interrogation system and one single-antenna PIT tag interrogation system (Figure 2). The multi-antenna PIT tag interrogation system (hereafter, upper interrogator [UI]) was deployed 30 m upstream of the LSW. The UI consisted of one Digital Angel Model FS-1001M multiplexing PIT tag transceiver, six custom-made antennas, and a DC power source. The six antennas were arranged longitudinally in three arrays (2 antennas/array), which (1) allowed us to determine direction of fish movement, (2) enhanced the efficiency of detection, and (3) ensured coverage of the entire wetted width of the stream during the majority of summer flow levels. At the upstream-most array (array A), we installed a 1.8- $\times$ 0.9-m antenna (number 1) on river left and a 3.1- $\times$ 0.9-m antenna (number 2) on river right. At the middle array (array B), we installed two 3.1- $\times$ 0.9-m antennas (numbers 3 and 4). For the downstream array (array C), we installed two 1.8- $\times$ 0.9-m antennas (numbers 5 and 6). Arrays A and C were installed in a pass-by configuration, while array B was installed in a hybrid configuration as described by Connolly et al. (2008). Array A was 8.2 m upstream from array B, and array B was 14.6 m upstream from array C. The total distance from array A to array C was 22.8 m. The UI had detection efficiencies that exceeded 96% during high-flow periods and approached 100% during low-flow periods (Connolly et al. 2008). Downstream from the UI, the single-antenna PIT tag interrogator (hereafter, lower interrogator [LI]) was installed just downstream of the LSW at Beaver Creek rkm 4 during fall 2005 (Figure 2). The LI consisted of a Digital Angel Model 2001F-ISO PIT tag transceiver, a 12-V battery, and a small (1.2 $\times$ 0.6 m) antenna.

To assess discharge, a MiniTroll pressure transducer (In Situ Corporation, Fort Collins, Colorado) was deployed 5 m upstream of the LSW. The pressure transducer recorded water depths at 20-min intervals. These readings along with instream flow calculations were used to develop a rating curve to estimate stream discharge at the diversion weirs (Ruttenberg 2007). Water depths were collected by the University of Idaho during July 2004 through May 2006 (when high flows washed out the pressure transducer). The U.S. Geological Survey reinstalled the pressure transducer in March 2007 and recorded stream levels through December 2007.

Upstream movement at LSW was determined based on detections of fish at the UI, but for our analysis we limited the data to fish detected at both the LI and UI. The timing of upstream passage was matched with the discharge readings taken just upstream of the LSW. Due to limited presence and PIT tagging of other fish species in Beaver Creek, our analyses of length and movement were focused on steelhead and rainbow trout (hereafter referred to collectively as *O. mykiss*, as we did not distinguish between the two forms).

Because *O. mykiss* were not physically recaptured upstream of the LSW, individual fish lengths at the time of passage were not available. To evaluate the size of fish passing the LSW, we adjusted fish length based on each fish's length at tagging and the growth of recaptured fish. We used PIT tag recapture data collected during three common sampling periods (spring, summer, and fall) from two locations (fish trap or electrofishing near rkm 1; electrofishing near the LSW between rkm 3 and rkm 5). The number of days from tagging to a fish passage event was then separated into growth periods (March–May, June–August, and September–February). If a fish was detected in both the LSW and fish trap areas, we used the average daily growth for each area and each growth period to adjust the fork length (FL) at the time of passage. If a fish was tagged and thought to remain in the LSW area, we used the average daily growth for the LSW area to adjust FL. Finally, we multiplied the number of days in each growth period by the appropriate average daily growth rate and added the total growth to the original FL. We refer to this new length as the adjusted FL (AFL).

We compared *O. mykiss* that moved from the LI to the UI (treatment section) with *O. mykiss* that moved from one UI array to another (array C to B, B to A, or C to A; control sections). If a fish was detected at all three arrays, we only used the distance from array C to array A. We evaluated the distribution of *O. mykiss* passage time for normality and found it to be positively skewed; therefore, we $\log_{10}$ transformed the data. To account for differences in reach length between the treatment section (141 m) and control sections (distances were 14.6 m between arrays C and B, 8.2 m between arrays B and A, and 22.8 m between arrays

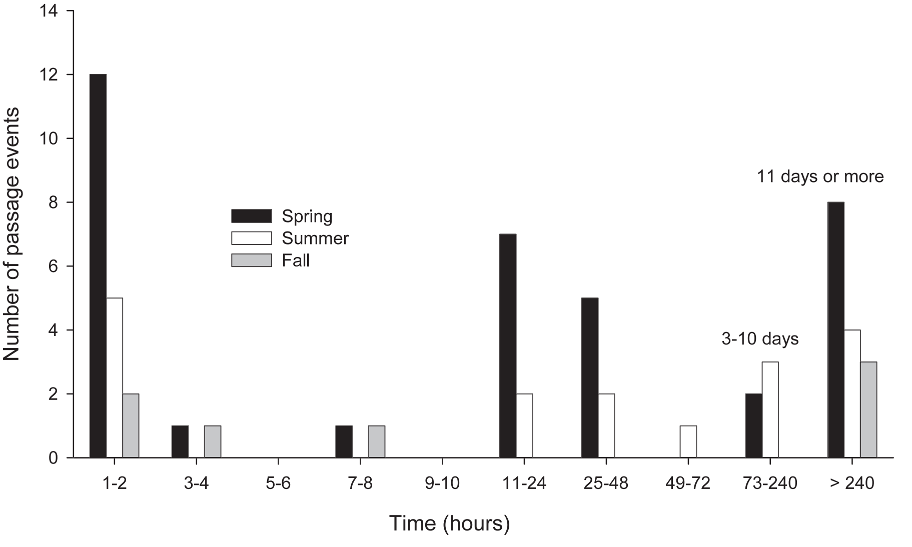

FIGURE 3.—Amount of time (h) taken by juvenile steelhead or rainbow trout (86–238 mm adjusted fork length) to move upstream through the series of rock vortex weirs at the Lower Stokes Water Diversion. No fish were observed to move through the rock vortex weirs in the winter.

C and A), we used the ratio of distance over time. We separated our fish passage data for treatment and control sections into four categories (low discharge and slow-moving fish, high discharge and slow-moving fish, low discharge and fast-moving fish, and high discharge and fast-moving fish). Discharge was separated into high and low categories on the first occasion that the discharge level doubled from the previous discharge rate (0.31–0.64 m^3/s) for fish passing the RVWs. Fast- and slow-moving fish were separated based on one SD over the mean movement rate (i.e., mean + SD = 2.2 m/min) of fish passing through the RVWs. The treatment and control data sets were then used to run a chi-square analysis to compare movement rates between the two discharge rates (low discharge = 0.15–0.31 m^3/s; high discharge = 0.64–2.93 m^3/s). Finally, we ran a linear regression to evaluate whether passage time was size dependent.

Results

We PIT-tagged a total of 6,596 *O. mykiss*, Chinook salmon, coho salmon, bull trout, brook trout, mountain whitefish, and bridgelip suckers. Of this total, 5,172 fish were small (<240 mm FL) *O. mykiss*, of which 3,699 were captured, tagged, and released downstream of the RVWs and LI. After the modification of the downstream-most water diversion (Fort Thurlow), new species collected by electrofishing or detected upstream of the LSW included juvenile Chinook salmon (n = 24), juvenile coho salmon (n = 2), and mountain whitefish (n = 1). Five small *O. mykiss* and one brook trout that were tagged and released below the LSW were recaptured through electrofishing just upstream of the UI. During 2005–2007, we recorded 109 events of upstream fish passage by small salmonids at the UI, including 88 *O. mykiss*, 20 brook trout, and 1 coho salmon. The smallest documented upstream mover (one *O. mykiss* that was 77 mm FL when tagged at the fish trap) was detected at the UI upstream of the RVWs less than 2 months after it was tagged.

Of the 88 upstream passage events of *O. mykiss*, 60 involved detection of fish at the LI and subsequent detection at the UI. The duration of these *O. mykiss* movements through the LSW ranged from 28 min to 85 d. Most of these fish moved through the LSW in the spring and summer, whereas little to no movement occurred during the fall and winter months (Figure 3). Small *O. mykiss* ranging from 86 to 238 mm AFL were detected as moving through the LSW (from LI to UI) within 1 h of first detection at the LI at discharges as low as 0.15 m^3/s. Since deployment of the LI in fall 2005, we did not record discharge levels less than 0.15 m^3/s. Corresponding flow records were available for 46 of the 60 *O. mykiss* that were detected at both the LI and UI. These 46 passage events with flow records were used in our comparison of treatment and control sections.

From October 2005 to September 2007, the LI detected 107 small *O. mykiss*, 98 of which had been tagged near (within 20 m of) the LI. Thirteen small *O.*

mykiss detected at the UI were originally tagged at the fish trap (rkm 1), which constituted an upstream movement of more than 3 km. Of these 13 *O. mykiss*, nine (70%) were previously detected at the LI; these nine fish ranged in size from 77 to 208 mm FL and took 28 min to 85 d to pass through the LSW.

At both high and low discharges, the number of slow-moving fish passing through the treatment section was greater than the number moving through the control sections (Figure 4). Fish passing the treatment section moved more slowly ($\chi^2 = 3.9781$, $P = 0.046$) at low discharge versus high discharge, but no such difference ($\chi^2 = 0.023$, $P = 0.880$) was found for fish moving through the control sections. There was no evidence for size dependence in movement rate through the LSW at either low discharge ($r^2 = 0.049$, $P = 0.564$) or high discharge ($r^2 = 0.003$, $P = 0.774$).

Discussion

We found three additional species of fish above the LSW after its modification: juvenile Chinook salmon, juvenile coho salmon, and mountain whitefish. Although the observed number of fish from formerly excluded species was relatively low (<30), the numbers are likely to increase in the future. Access to new rearing area for these juvenile salmonids will hopefully lead to a sustained process of colonization. Anderson et al. (2008) speculated that juvenile salmonids using nonnatal streams may increase colonization if they return as adults to their rearing sites rather than to their emergence sites. In addition, enhanced tributary access may provide additional benefits to juvenile salmonids in comparison with rearing that is confined to the main-stem river. Murray and Rosenau (1989) observed that juvenile Chinook salmon that moved into nonnatal tributaries experienced increased growth compared with fish rearing in a main-stem river, while Ebersole et al. (2006) reported that juvenile coho salmon had greater overwinter growth and survival in tributaries than in a main-stem river.

We successfully monitored over 100 small fish moving upstream and past a series of RVWs at our LSW site. Small *O. mykiss* ranging from 86 to 238 mm AFL were able to move through the LSW within 1 h, but some took much longer (up to 98 d). The increase in the number of species and the recorded movements of small *O. mykiss* through the LSW indicated that the RVWs were effective at passing small fish upstream. However, the modification appeared just as effective in allowing small-sized fish of an introduced salmonid species, brook trout, to pass upstream.

Small fish were able to move through the RVWs at low discharge levels as documented by the passage of *O. mykiss* as small as 77 mm through the LSW when discharge was at the lowest recorded level. Fish passing upstream through the treatment section at low discharge took a longer time than fish passing upstream through a control section. The treatment and control sections did differ in character. The control sections were more representative of a low-gradient pool–riffle complex, while the treatment section was more representative of a high-gradient pool–riffle complex. Ovidio and Philippart (2002) found that areas downstream of blockages provided good habitat for several species of fish, and Jungwirth (1996) observed that fish in pools created by natural-style passage structures were found in the same pool for months after initial sampling. The range in travel time (from 28 min to over 98 d) through the LSW may be related to the pools created downstream of each RVW, which could provide good habitat for the fish and less motivation for instream movement.

We could not identify the number of fish that made unsuccessful attempts to pass upstream and over the LSW. However, all nine *O. mykiss* (77–208 mm FL) that expressed definitive upstream movement (fish that moved distances >3 km) from the fish trap to the LI were also detected at the UI, upstream of the LSW. In addition, we found no evidence that fish were unsuccessful in their attempts to pass upstream and over the LSW (i.e., fish moving upstream from the fish trap and detected at the LI but not at the UI). Because the proportion of fish detected as moving upstream was reasonably high (70%) at the LI, we would expect that if fish were unsuccessful in their attempts to pass the RVWs, some individuals would have been detected at the LI as moving back downstream. No fish were observed to move back downstream. Nonetheless, our design was probably better at recording success rather than failure of passage through the series of RVWs.

It is difficult to decipher failure because small *O. mykiss* in our study could not be assumed to have a definitive motivation for moving upstream, unlike the upstream movement of adult steelhead near spawning time or the downstream movement of steelhead smolts. Cargill (1980) reported that wild rainbow trout in small streams exhibited no significant upstream or downstream movement after 2.5 years. Furthermore, Helfrich and Kendall (1982) found that hatchery-released rainbow trout in a mountain stream showed mostly local movements within 1 km of their stocking locations and that most of the fish moved downstream. Although Leider et al. (1986) provided some evidence of upstream movement (up to 2 km) by presmolt steelhead, most parr emigrated downstream. McMichael and Pearsons (2001) reported that residual hatchery steelhead moved over 12 km upstream. The relatively low portion of *O. mykiss* that were tagged at

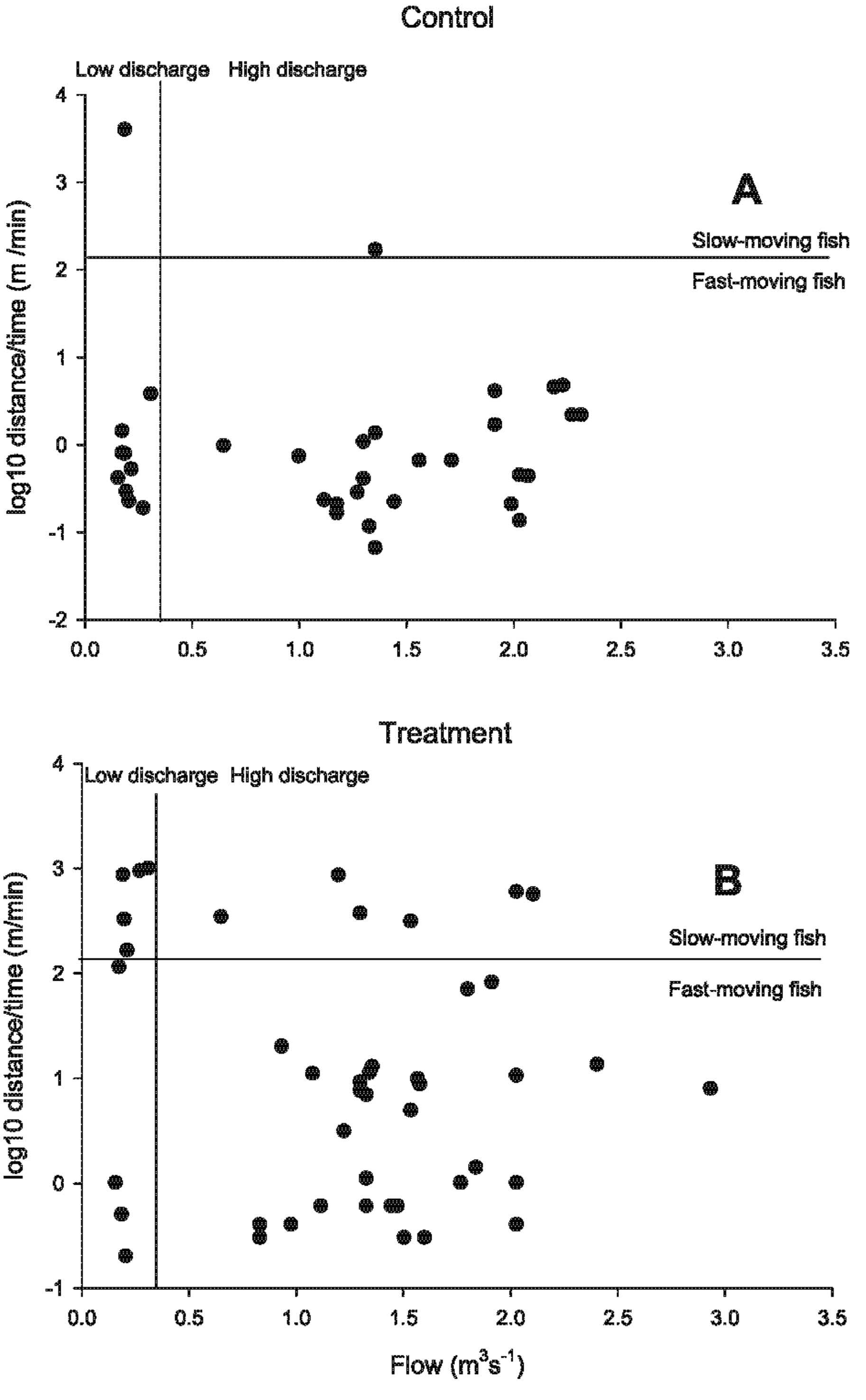

FIGURE 4.—Upstream fish passage events for fast- and slow-moving ($\log_{10}$[distance/time]) juvenile steelhead or rainbow trout during low and high flows at **(A)** a set of passive integrated transponder (PIT) tag antennas (control sections) and **(B)** a series of rock vortex weirs (treatment section).

the fish trap (>3 km downstream) and detected (13 fish) or recaptured (5 fish) at or above the RVWs indicates that small *O. mykiss* lacked motivation to move large distances upstream in Beaver Creek.

Water use in eastern Oregon and Washington has increased as irrigation has made large areas of land more useful for agriculture (Wissmar et al. 1994). Farmers and ranchers have come to rely on this water to grow crops and raise cattle. Unfortunately, the increase in irrigation via water diversions has often been at the expense of threatened and endangered aquatic species. Habitat enhancement measures, such as installation of RVWs, have been widely implemented to reduce human impacts, but the effectiveness of RVWs for fish had not been well documented (Roni et al. 2002) due to the lack of funding and appropriate methodologies to conduct definitive studies. Our work demonstrates an effective method for testing these enhancement measures and shows that RVWs are effective at passing small fish upstream. Modification of a century-old barrier helped to restore longitudinal connectivity of depressed native salmonid populations, but it also facilitated movement by brook trout, an introduced species.

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References

Aarestrup, K., M. C. Lucas, and J. A. Hasen. 2003. Efficiency of nature-like bypass channel for sea trout (*Salmo trutta*) ascending a small Danish stream studied by PIT telemetry. Ecology of Freshwater Fish 12:160–168.

Anderson, J. H., P. M. Kiffney, G. R. Pess, and T. P. Quinn. 2008. Summer distribution and growth of juvenile coho salmon during colonization of newly accessible habitat. Transactions of the American Fisheries Society 137:772–781.

Bednarek, A. T. 2001. Undamming rivers: a review of the ecological impacts of dam removal. Environmental Management 27:803–814.

Belford, D. A., and W. R. Gould. 1989. An evaluation of trout passage through six highway culverts in Montana. North American Journal of Fisheries Management 9:437–445.

Bryant, M. D., M. D. Lukey, J. P. McDonell, R. A. Gubernick, and R. S. Aho. 2009. Seasonal movement of Dolly Varden and cutthroat trout with respect to stream discharge in a second-order stream in Southeast Alaska. North American Journal of Fisheries Management 29:1728–1742.

Bunt, C. M., C. Katopodis, and R. S. McKinley. 1999. Attraction and passage efficiency of white suckers and smallmouth bass by two denil fishways. North American Journal of Fisheries Management 19:793–803.

Calles, E. O., and L. A. Greenberg. 2005. Evaluation of nature-like fishways for reestablishing connectivity in fragmented salmonid populations in the river Eman. River Research and Applications 21:951–960.

Calles, E. O., and L. A. Greenberg. 2007. The use of two nature-like fishways by some fish species in the Swedish river Eman. Ecology of Freshwater Fish 16:183–190.

Cargill, A. S. II. 1980. Lack of rainbow trout movement in a small stream. Transactions of the American Fisheries Society 109:484–490.

Connolly, P. J., I. G. Jezorek, K. D. Martens, and E. F. Prentice. 2008. Measuring performance of two stationary interrogation systems for detecting downstream and upstream movement of PIT-tagged salmonids. North American Journal of Fisheries Management 28:402–417.

Connolly, P. J., and S. T. Sauter. 2008. The role of barriers in the abundance and persistence of coastal cutthroat trout in the Columbia River gorge. Pages 60–61 *in* P. J. Connolly, T. H. Williams, and R. E. Gresswell, editors. The 2005 coastal cutthroat trout symposium: status, management, biology and conservation. American Fisheries Society, Oregon Chapter, Portland.

Curry, R. A., C. Brady, D. L. G. Noakes, and R. G. Danzmann. 1997. Use of small streams by young brook trout spawned in a lake. Transactions of the American Fisheries Society 126:77–83.

Detenbeck, N. E., P. W. DeVore, G. J. Niemi, and A. Lima. 1992. Recovery of temperate-stream fish communities from disturbance: a review of case studies and synthesis of theory. Oecologia 16:33–53.

Ebersole, J. L., P. J. Wigington, J. P. Baker, M. A. Cairns, M. R. Church, B. P. Hansen, B. A. Miller, H. R. LaVigne, J. E. Compton, and S. G. Leibowitz. 2006. Juvenile coho salmon growth and survival across stream network seasonal habitats. Transactions of the American Fisheries Society 135:1681–1697.

Erkinaro, J., M. Julkunen, and E. Niemelä. 1998. Migration of juvenile Atlantic salmon *Salmo salar*, in small tributaries of the subartic river Teno, northern Finland. Aquaculture 168:105–119.

FAO/DVWK (Food and Agriculture Organization of the United Nations/Deutscher Verband fur Wasserwirtschaft and Kulturbau e. V.). 2002. Fish passes: design, dimensions and monitoring. FAO, Rome. Available: www.fao.org/docrep/010/y4454e/y4454e00.htm. (September 2010).

Ficke, A. D., and C. A. Myrick. 2009. A method for monitoring movements of small fishes in urban streams. North American Journal of Fisheries Management 29:1444–1453.

Harvey, B. C. 1991. Interaction among stream fishes: predator-induced habitat shifts and larval survival. Oecologia 87:29–36.

Helfrich, L. A., and W. T. Kendall. 1982. Movements of hatchery-reared rainbow, brook, and brown trout stocked in a Virginia mountain stream. Progressive Fish-Culturist 44:3–7.

Jungwirth, M. 1996. Bypass channels at weirs as appropriate aids for fish migration in rhithral rivers. Regulated Rivers Research and Management 12:483–492.

Leider, S. A., M. W. Chilcote, and J. J. Loch. 1986. Movement and survival of presmolt steelhead in a tributary and the main stem of a Washington river. North American Journal of Fisheries Management 6:526–531.

Martens, K. D., and P. J. Connolly. 2008. Lower Methow tributaries intensive effectiveness monitoring study. U.S. Geological Survey, Western Fisheries Research Center, Columbia River Research Laboratory, Interim Report, Cook, Washington.

McMichael, G. A., and T. N. Pearsons. 2001. Upstream movement of residual hatchery steelhead into areas containing bull trout and cutthroat trout. North American Journal of Fisheries Management 21:943–946.

Murray, C. B., and M. L. Rosenau. 1989. Rearing of juvenile Chinook salmon in nonnatal tributaries of the lower Fraser River, British Columbia. Transactions of the American Fisheries Society 118:284–289.

Neville, H. M., J. B. Dunham, and M. M. Peacock. 2006. Landscape attributes and life history variability shape genetic structure of trout populations in a stream network. Landscape Ecology 21:901–916.

NMFS (National Marine Fisheries Service). 2000. Guidelines for salmonid passage at stream crossings. U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Southwest Region, Final Draft, Long Beach, California.

Ovidio, M., and J. Philippart. 2002. The impact of small physical obstacles on upstream movements of six species of fish. Hydrobiologia 482:55–69.

Roni, P., T. J. Beechie, R. E. Bilby, F. E. Leonetti, M. M. Pollock, and G. R. Pess. 2002. A review of stream restoration techniques and a hierarchical strategy for prioritizing restoration in Pacific Northwest watersheds. North American Journal of Fisheries Management 22:1–20.

Ruttenberg, D. 2007. An evaluation of fish passage at rock vortex weirs. Master's thesis. University of Idaho, Moscow.

Schmetterling, D. A., R. W. Pierce, and B. W. Liermann. 2002. Efficacy of three denil fish ladders for low-flow fish passage in two tributaries to the Blackfoot River, Montana. North American Journal of Fisheries Management 22:929–933.

Scrivener, J. C., T. G. Brown, and B. C. Andersen. 1993. Juvenile Chinook salmon (*Oncorhynchus tshawytscha*) utilization of Hawks Creek, a small and nonnatal tributary of the upper Fraser River. Canadian Journal of Fisheries and Aquatic Sciences 51:1139–1146.

SMRC (Stormwater Manager's Resource Center). 2008. Stream restoration: grade control practices. Available: stormwatercenter.net/Assorted%20Fact%20Sheets/Restoration/grade_control.htm. (November 2008).

USBOR (U.S. Bureau of Reclamation). 2004a. Lower Stokes fish passage improvement project, Beaver Creek, Methow subbasin, Washington. USBOR, Completion Report, Boise, Idaho. Available: www.usbr.gov/pn/programs/farps/thp/ucao/index.html. (December 2010).

USBOR (U.S. Bureau of Reclamation). 2004b. Thurlow Transfer Ditch, fish passage improvement project, Beaver Creek, Methow subbasin, Washington. USBOR, Completion Report, Boise, Idaho. Available: www.usbr.gov/pn/programs/farps/thp/ucao/index.html. (December 2010).

USBOR (U.S. Bureau of Reclamation). 2004c. Upper Stokes fish passage improvement project, Beaver Creek, Methow subbasin, Washington. USBOR, Completion Report, Boise, Idaho. Available: www.usbr.gov/pn/programs/farps/thp/ucao/index.html. (December 2010).

USBOR (U.S. Bureau of Reclamation). 2005. Fort-Thurlow diversion dam fish passage improvement project, Beaver Creek, Methow subbasin, Washington. USBOR, Completion Report, Boise, Idaho. Available: www.usbr.gov/pn/programs/farps/thp/ucao/index.html. (December 2010).

USFS (U.S. Forest Service). 2004. Beaver Creek stream survey report 2004. Okanogan-Wenatchee National Forest, Methow Ranger District, Winthrop, Washington.

Warren, M. L., and M. G. Pardew. 1998. Road crossings as barriers to small-stream fish movement. Transactions of the American Fisheries Society 127:637–644.

WDFW (Washington Department of Fish and Wildlife). 2000. Fish passage barrier and surface water diversion screening assessment and prioritization manual. WDFW, Habitat and Lands Programs, Environmental Engineering Division, Olympia.

Winston, M. R., C. M. Taylor, and J. Pigg. 1991. Upstream extirpation of four minnow species due to damming of a prairie stream. Transactions of the American Fisheries Society 120:98–105.

Wissmar, R. C., J. E. Smith, B. A. McIntosh, H. W. Li, G. H. Reeves, and J. R. Sedell. 1994. Ecological health of river basins in forested regions of eastern Washington and Oregon. U.S. Forest Service General Technical Report PNW-GTR-326.