Effectiveness of a redesigned water diversion using rock vortex weirs to enhance longitudinal connectivity for small salmonids

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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 2000-2004, four dam-style water diversions were replaced with a series of rock vortex weirs. These 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 rock vortex weirs indicating successful restoration of longitudinal connectivity. We used passive integrated transponder (PIT) tags and instream PIT tag interrogators during 2004-2007 to evaluate upstream passage of small salmonids (< 240 mm FL) through one of these series of rock vortex weirs. We documented 109 upstream passage events by small salmonids through the series of rock vortex weirs, most of which (81%) were rainbow trout/juvenile steelhead *O. mykiss*. Small rainbow trout/steelhead ranging from 86 – 238 mm were able to pass upstream through the rock vortex weir, though a delay in fish passage at discharges below 0.32 m^3s^{-1} was detected when compared to a nearby control section.

Introduction

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). They 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 fish barriers on fish movement in the Pacific Northwest is the blockage of adult salmonid access to their 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), to refugia from predation (Harvey 1991), and to colonization of fish populations following 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 with 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 (VIE) tags (Schmetterling et al. 2002; Ficke and Myrick 2009), acrylic paint injection (Warren and Pardew 1998), and radio telemetry (Bunt et al. 1999; Ovidio and Philippart 2002) have serious limitation for determining fish direction and timing. Floy tags, VIE tags, and acrylic injection techniques could not provide information regarding specific travel times through the rock vortex weirs (RVW) unless traps were continuously operated upstream and downstream of the diversion. The use of radio telemetry can provide travel-time data; however, the number and size of fish can be limited due to the size, cost, and lifespan of the tags. Passive integrated transponder (PIT) tags and fixed instream interrogation systems can be used to determine direction and the exact time of fish movement (Connolly et al. 2008), to relate the time of movement to near instantaneous stream flow 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 a lot of potential for these types of studies.

Passive integrated transponder tags and instream interrogators have been successfully used to study natural-style passage structures using large (> 250 mm) migratory fish (Aarestrup et al. 2003; Calles and Greenberg 2007), but few studies have looked at small fish that may or may not have migratory tendencies. Fish passage through RVW has received little attention in laboratory and field studies (Ruttenberg 2007). Structures such as RVW 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 are the variety of flows and depths for movement of different species and sizes of fish, as well as the habitat they create (Aarestrup et al. 2003). Previous evaluations of these types of 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 RVW for instream restoration increases, their effectiveness needs to be assessed to justify large expenditures and to prevent replicating flawed designs. The objectives of this study were to: 1) assess the effectiveness of a series of RVW to pass upstream passage of small fish, and 2) assess role of stream discharge and fish length on speed and timing of fish moving through the series of RVW.

Study Area

Our study was conducted in Beaver Creek, a tributary of the lower Methow River in northcentral Washington State, USA (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, WA. The watershed area is 179 km^2 (USFS 2004) and ranges in elevation from 463 to 1,890 m. Discharge in Beaver Creek was typically highest in May and June, and then declined to base levels during August - October. During July 2004 and September 2007, the lowest daily median discharge was 0.05 m^3s^{-1} in September 2005, and the highest daily median discharge was 4.70 m^3s^{-1} in 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 RVW (USBOR 2004a, 2005). The RVW in Beaver Creek were designed and installed under the supervision of U.S. Bureau of Reclamation to meet fish passage standards established by the National Marine Fisheries Service (NMFS 2000) and Washington Department of Fish and Wildlife (WDFW 2000).

Modifications to the water diversions in Beaver Creek included installing a series of RVW at a given site (USBOR 2004a, 2004b, 2004c, 2005). These RVW 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 degrees relative to the stream bank (Figure 1). Footer stones were installed along rock layers and weir stones were positioned above them. Rock vortex weirs were designed in hopes 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 RVW typically created scour pools downstream of the weirs, which had the potential to provide rearing habitat and a jump pool for fish. While RVW are not new (Roni et al 2002), their effectiveness for allowing upstream passage of small fish was largely unknown and is likely to vary among sites.

Before the construction of the Lower Stokes water diversion (LSW), rainbow trout/steelhead *Oncorhynchus mykiss*, eastern brook trout *Salvelinus fontinalis*, and shorthead sculpin *Cottus confusus* could be found just upstream of the LSW. Downstream of the LSW, anadromous salmonids (primarily steelhead, but also Chinook salmon *O. tshawytscha* and coho salmon *O. kisutch*), non-anadromous salmonids (rainbow trout, westslope cutthroat trout *O. clarki*, bull trout *S. confluentus*, mountain whitefish *Prosopium williamsoni* and eastern brook trout), and non-salmonids (shorthead sculpin, longnosed dace *Rhinichthys cataractae*, bridgelip sucker *Catastomus columbianus*, and smallmouth bass *Micropterus dolomieu*) were present (Martens and Connolly 2008).

Methods

Fish were collected using a two-way fish trap at rkm 1 (Figure 2) and backpack electrofishers. In order to track movements, most fish 65 mm or longer were tagged with a 12.5 mm PIT tag (full duplex, 134.2 kHz). 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 in 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 RSW. The two-way fish trap was operated from 22 October through 22 December (60 d) in 2004, from 20 March through 5 December (253 d) in 2005, from 13 February through 27 April and 28 June through 27 November (220 d) in 2006, and from 24 February through 30 March and 25 May through 30 September (219 d) in 2007. The trap was checked a minimum of once a day. Trap operations were typically compromised by high flows during the fall and early spring. The trap was pulled in winters due to ice accumulations. Fish trapping operations started in late fall 2004 and ran into fall 2007.

We maintained and operated one multi-antenna and multiplexing PIT tag interrogation system and one single-antenna PIT tag interrogation system (Figure 2). The multi-antenna PIT tag interrogation system or upper interrogator (UI) was deployed 30 m upstream of the LSW. The UI consisted of a FS 1001M Digital Angel multiplexing PIT tag transceiver, six custom-made antennas, and a DC power source. The six antennas were arranged longitudinally in three arrays, with two antennas per array, which allowed us to determine direction of fish movement, to enhance efficiency of detection, and to insure 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-m x 0.9-m antenna (number 1) on river left and a 3.1-m x 0.9-m antenna (number 2) on river right. At the middle array (array B) we installed two 3.1-m x 0.9-m antennas (numbers 3 and 4), and for the downstream array (array C), we installed two 1.8-m x 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 at. (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 and array C was 22.8 m. This interrogator had detection efficiencies exceeding 96% during high flow periods and approached 100% during low flow periods (Connolly et al. 2008). Downstream from the UI, a single-antenna PIT tag interrogator (LI) was installed just downstream of the LSW at rkm 4 in Beaver Creek during fall 2005 (Figure 2). The single-antenna, PIT tag interrogation system consisted of a 2001F-ISO Digital Angel PIT tag transceiver, a 12-volt battery, and a small (1.2 m x 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-minute 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 from July 2004 through May 2006 (when high flows washed out the pressure transducer) by the University of Idaho. The U. S. Geological Survey (USGS) reinstalled the pressure transducer in March 2007 and recorded stream levels through December 2007.

Upstream movement for LSW was determined by fish detected 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 species of fish in Beaver Creek, we focused our length and movement analysis on *O. mykiss*.

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

Stokes area to adjust fork length. 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 fork length. We refer to this new length as "adjusted fork length" (AFL).

We compared *O. mykiss* moving from the LI to the UI (treatment section) to *O. mykiss* moving from one array to another (Array C-B, B-A or C-A) of the UI (control sections). If a fish was detected at each array, we only used the distance from array C to array A. We evaluated the distribution of passage time of *O. mykiss* for normality and found it to be positively skewed; therefore, we log-transformed the data. To account for differences in length between the treatment and control sections (distance of the treatment section was 141 m, distance between Array C to B was 14.6 m, between Array B to A was 8.2 m, and between Array C to A was 22.8 m), 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 to 0.64 m^3s^{-1}) of fish passing the RVW. Fast and slow moving fish were separated based on one standard deviation over the mean (mean + SD = 2.2 m/min) of fish passing through the RVW. The treatment and control data sets were then used to run a Chi-square analysis to compare movement rates between two discharge rates (low discharge 0.15 – 0.31 m^3s^{-1}, high discharge 0.64 – 2.93 m^3s^{-1}). Finally, we ran a linear regression to evaluate whether passage time was size dependant.

Results

We PIT tagged a total of 6,596 juvenile steelhead/resident rainbow trout, Chinook salmon, coho salmon, bull trout, brook trout, mountain whitefish, and bridgelip sucker. Of these, 5,172 were small (< 240 mm) *O. mykiss* with 3,699 captured, tagged, and released downstream the RVW and LI. Following 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. From 2005 through 2007, we recorded 109 upstream fish passage events of small salmonids at the UI, including: 88 *O. mykiss*, 20 brook trout, and 1 coho salmon. The smallest documented upstream mover (a 77 mm *O. mykiss* when tagged at the fish trap) was detected upstream of the RVW at the UI less than two months after it was tagged.

A total of 60 of the 88 upstream passage events of *O. mykiss* were detected at the LI and subsequently detected at the UI. 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, with little to no movement occurring during the fall and winter months (Figure 3). Small *O. mykiss* ranging from 86-238 mm (AFL) were detected moving through the LSW (LI to UI) within one hour of first detection at the LI, at discharges as low as 0.15 m^3s^{-1}. Since deployment of the LI in fall 2005, we did not record discharge under 0.15 m^3s^{-1}. Corresponding flow records were available for 46 of the 60 *O. mykiss* that were detected at both 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 this interrogator (within 20 meters). We detected 13 small *O. mykiss* at the UI that were originally tagged at fish trap (rkm 1), which constituted a movement upstream > 3 km. Of these 13 *O. mykiss* that moved, 9 (70%) were previously detected at the LI. These nine fish detected at the LI that were subsequently detected at the UI range in size (77-208 mm FL) and took 28 min to 85 days to pass through the LSW.

There were more slow-moving fish at both high and low discharge moving over the treatment section compared to the control section (Figure 4). Fish passing the treatment section moved slower (X^2 = 3.9781, P= 0.046) when moving at low discharge versus high discharge, but no such difference (X^2 = 0.023, P = 0.880) was found for fish moving through the control section. 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

After modification of the LSW, we found three additional species of fish above it: juvenile Chinook salmon, juvenile coho salmon, and mountain whitefish. While the number of fish we observed from formerly excluded species were relatively low (< 30), their 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 their emergent sites. In addition, enhanced tributary access may provide additional benefits to juvenile salmonids compared to rearing confined to the mainstem river. Murray and Rosenau (1989) observed that juvenile Chinook that moved into nonnatal tributaries experienced increased growth compared to fish rearing in a mainstem river, while Ebersole at al. (2006) reported that juvenile coho had improved growth and survival over winter in tributaries compared to those in a mainstem river.

We successfully monitored over 100 small fish moving upstream and past a series of RVW at our LSW site. Small *O. mykiss* ranging from 86-238 mm (AFL) were able to move through the LSW within 1 hr, but some took much longer (up to 98 days). The increase in the number of species and the recorded movements of small *O. mykiss* through the LSW indicated the RVW was 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 RVW at low discharges, as documented by a *O. mykiss* as small as 77 mm passing the LSW when discharges were at their lowest recorded level. Fish passing upstream through a treatment section at low discharge took a longer time compared to those passing upstream through a control section. These stream sections did differ in character. The control was 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 (28 min to over 98 d) through the LSW may be due to pools created downstream of each RVW providing good habitat for the fish and providing less motivation for instream movement.

We could not identify the number of fish that may have unsuccessfully attempted to pass upstream and over the LSW. However, all nine *O. mykiss* (77-208 mm FL) that expressed definitive upstream movement (fish that moved > 3 km) from the fish trap to LI were also detected upstream of the LSW at UI. In addition, there were no indications 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 LI, but not detected at the UI). Because the proportion of fish detected moving upstream was reasonably high (70%) at the LI, we would expect that if fish were unsuccessful in their attempts to pass the RVWs, there would have been some individuals detected at the LI moving back downstream. We did not observe any fish move back downstream. None the less, our design was likely better at recording success rather than failure of passage through the series of RVW.

It is difficult to decipher failure because small *O. mykiss* in our study could not be assumed to have a definitive motivation to move upstream, unlike upstream movement of adult steelhead near spawning time or downstream movement of steelhead smolts. Cargill (1980) reported that wild rainbow trout in small streams had 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. While Leider et al. (1986) provided some evidence of upstream movement of presmolt steelhead up to 2 km, most parr emigrated downstream. McMichael and

Pearsons (2001) observed residual hatchery steelhead moved over 12 km upstream. The relatively low number of *O. mykiss* tagged at the fish trap (> 3 km downstream) that were detected (13) and recaptured (5) at or above the RVW indicate that small *O. mykiss* lacked motivation to move large distances upstream in Beaver Creek.

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

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Literature Cited

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 stuied 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 secound-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. Oregon Chapter, American Fisheries Society, 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. Rome, FAO. 119p. Available: http://www.fao.org/docrep/010/y4454e/y4454e00.htm (9 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 & 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, Interim report. United States Geological Survey, Western Fisheries Research Center, Columbia River Research Laboratory. Cook, WA,

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. Final Draft. NOAA, U.S. Department of Commerce. Southwest Region, 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, College of Engineering, 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 (The Stormwater Manager's Resource Center). 2008. Stream restoration: grade control practices. Available:http://www.stormwatercenter.net/Assorted%20Fact%20Sheets/Restoration/grade_control.htm. (7 November 2008).

USBOR (U.S. Bureau of Reclamation). 2004a. Completion report, Lower Stokes fish passage improvement project, Beaver Creek, Methow subbasin, Washington. Boise, Idaho.

USBOR (U.S. Bureau of Reclamation). 2004b. Completion report, Thurlow Transfer Ditch, fish passage improvement project, Beaver Creek, Methow subbasin, Washington. Boise, Idaho.

USBOR (U.S. Bureau of Reclamation). 2004c. Completion report, Upper Stokes fish passage improvement project, Beaver Creek, Methow subbasin, Washington. Boise, Idaho.

USBOR (U.S. Bureau of Reclamation). 2005. Completion report, Fort-Thurlow diversion dam fish passage improvement project, Beaver Creek, Methow subbasin, Washington. Boise, Idaho.

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.

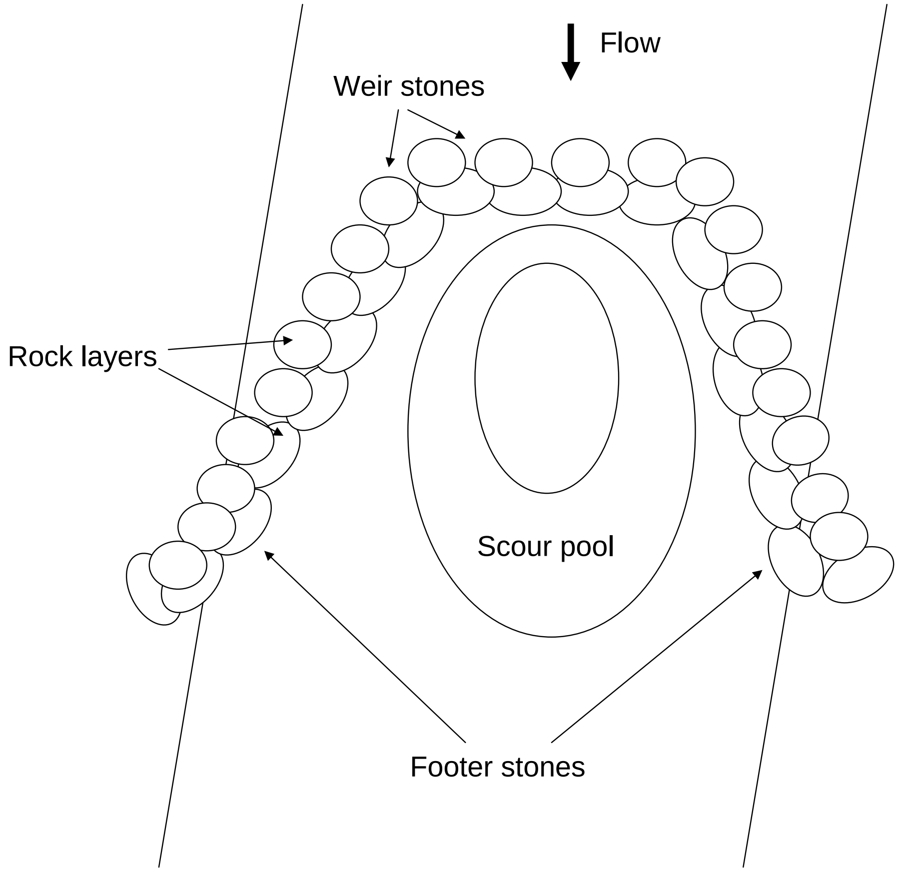
WDFW (Washington Department of Fish and Wildlife). 2000. Fish passage barrier and surface water diversion screening assessment and prioritization manual. Washington

Department of Fish and Wildlife, Habitat and Lands Programs, Environmental Engineering Division. Olympia, Washington.

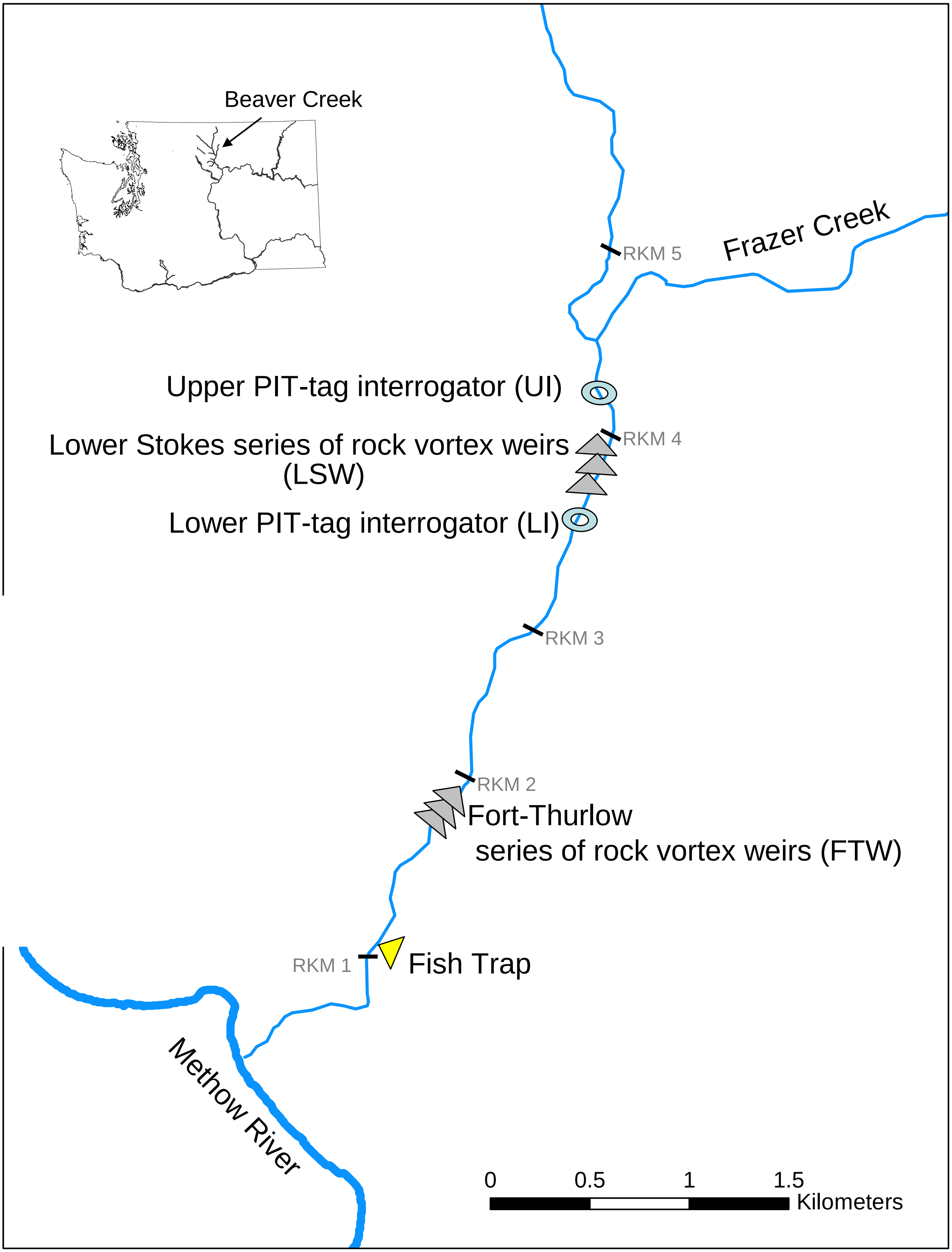
Winston, M. R., C. M. Taylor, and J. Pigg. 1991. Upstream extirpation of four minnow species due to damming of a prairie stream. Transactions of the American Fisheries Society 120:98-105.

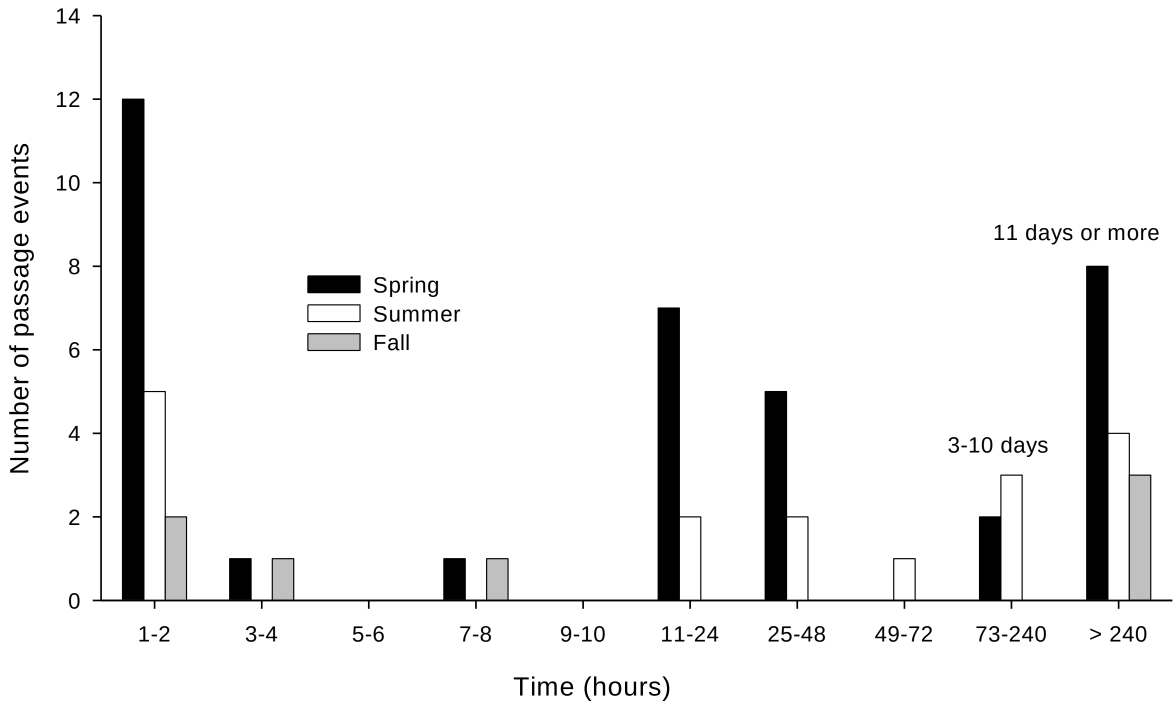
Wissmar, R. C., J. E. Smith, B. A. McIntosh, H. W. Li, G. H. Reeves, and J. R. Sedell. 1994. Ecological health of river basins in forested regions of eastern Washington and Oregon. General Technical Report PNW-GTR-326. U.S. Department of Agriculture, Forest Service. Pacific Northwest Research Station.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

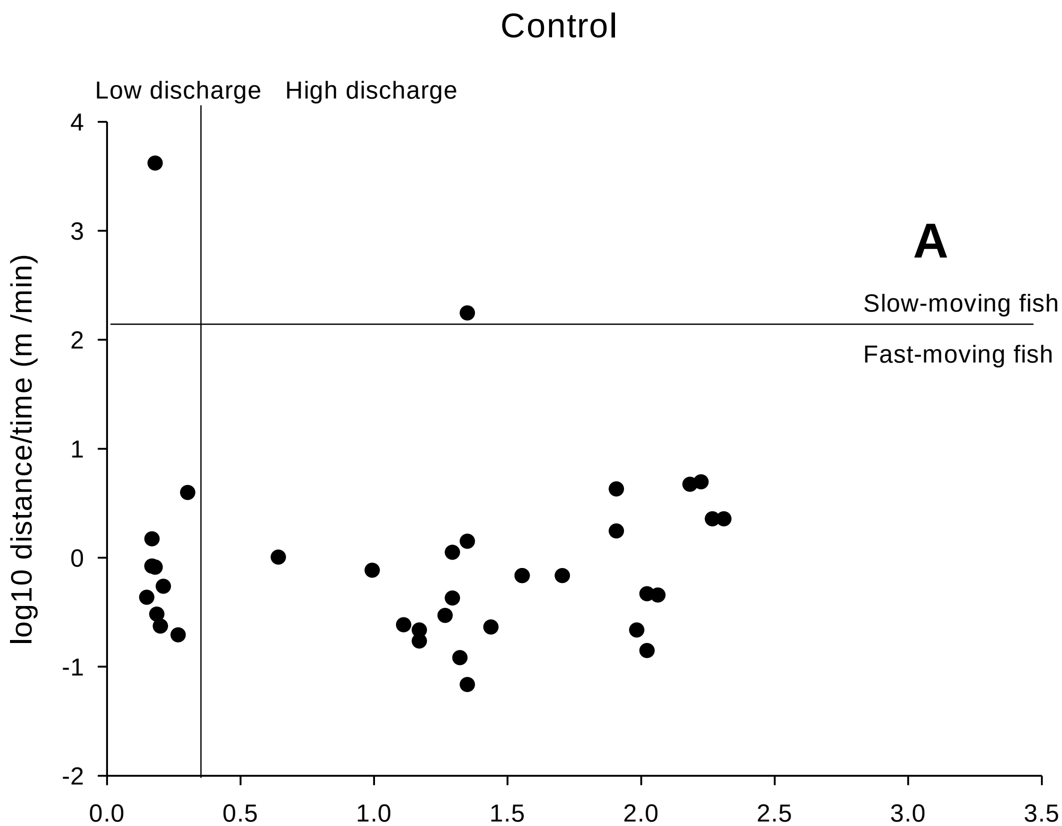
List of Figures

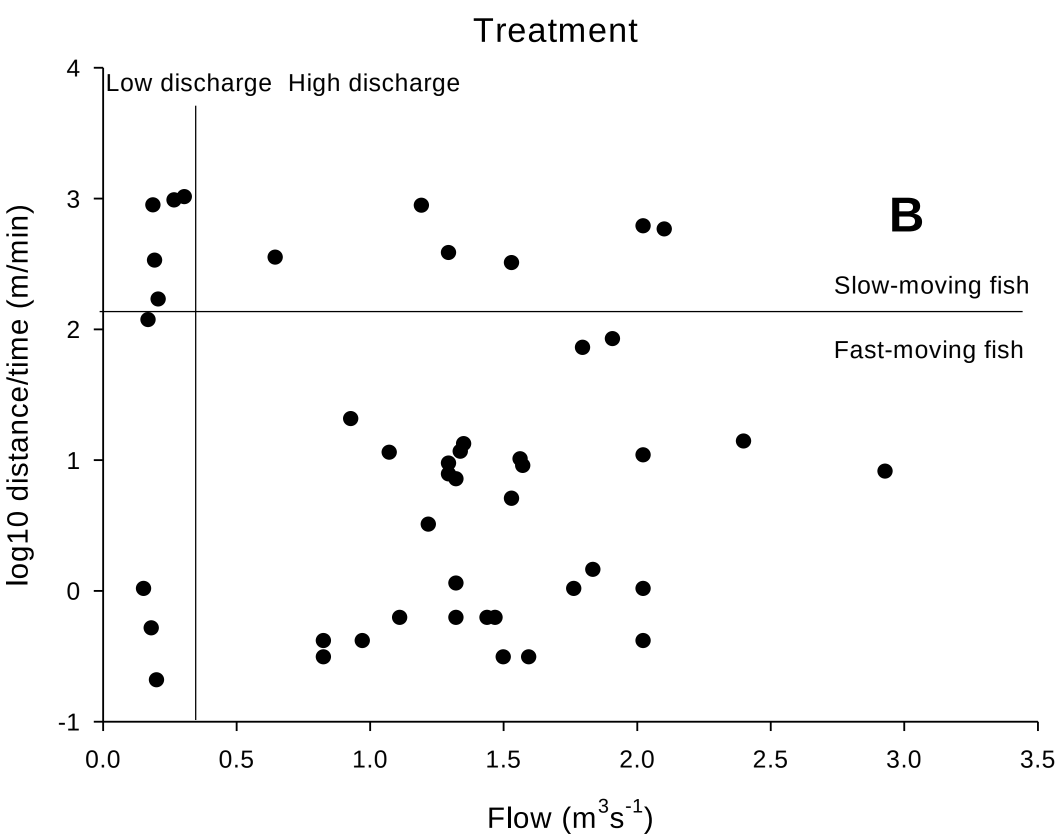


Flow
Weir stones
Rock layers
Scour pool
Footer stones


Beaver Creek
Frazer Creek
RKM 5
Upper PIT-tag interrogator (UI)
RKM 4
Lower Stokes series of rock vortex weirs
(LSW)
Lower PIT-tag interrogator (LI)
RKM 3
RKM 2
Fort-Thurlow
series of rock vortex weirs (FTW)
RKM 1
Fish Trap
Methow River
0
0.5
1
1.5
Kilometers


Number of passage events
Time (hours)
Spring
Summer
Fall
11 days or more
3-10 days
1-2
3-4
5-6
7-8
9-10
11-24
25-48
49-72
73-240
> 240
0
2
4
6
8
10
12
14


Control
Low discharge
High discharge
A
Slow-moving fish
Fast-moving fish
log10 distance/time (m /min)
4
3
2
1
0
-1
-2
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5


Treatment
Low discharge
High discharge
B
Slow-moving fish
Fast-moving fish
log10 distance/time (m/min)
4
3
2
1
0
-1
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
Flow (m3s-1)

528