

The influence of stream-crossing structures on the distribution of rearing juvenile Pacific salmon

Jeffrey C. Davis¹ AND Gay A. Davis¹

Aquatic Restoration and Research Institute, P.O. Box 923, Talkeetna, Alaska 99676 USA

Abstract. The effects of barriers to migration by adult salmon smolt have been well studied, but effects to migration of juvenile salmon during freshwater residency have not been evaluated thoroughly. We tested for differences in the relative abundance of juvenile Pacific salmon upstream and downstream of road-crossing culverts in 10 streams, 5 with moderate (upland) and 5 with low (wetland) slope. We compared stream width, bed slope, and substrate in natural channels and culverts; measured culvert water velocity during base flow; and obtained maximum and minimum culvert velocities using the flow time of dissolved solutes. We compared flow velocities to swimming speeds of rearing juvenile salmon to evaluate potential passage of fish through culverts. In upland streams with spawning adults, catch-per-unit-trap (CPUT) of juvenile coho salmon was often 2 to 3× greater above than below culverts. In these reaches, downstream migration of salmon fry from spawning locations may be limited by culvert flow velocities that exceed burst swimming speeds of juveniles. Where 2 upland crossing structures were replaced with culverts that replicated natural channel slopes, widths, and substrate, flow velocities decreased and differences in coho salmon CPUT were eliminated. In wetland streams with adult spawning reduced or absent above the crossing, CPUT of juveniles was greater below than above culverts where the outlet was perched. Thus, culverts can influence upstream and downstream fish movement and altered the distribution of rearing fish within streams.

Key words: fish passage, road culverts, coho salmon, migration.

Anthropogenic changes to the physical characteristics of streams can create complete or partial barriers to fish migration (Warren and Pardew 1998, Benton et al. 2008). Physical changes at sites where transportation corridors intersect streams include channel straightening, narrowing, or substrate modification—all of which can increase water velocities (Karle 2005) and may pose barriers to fish migration. Stream-crossing structures also alter stream physical characteristics and can generate water velocities that exceed fish swimming ability (Haro et al. 1998, 2004, Schaefer et al. 2003). Migration barriers affect fish production by eliminating or reducing access to large areas of spawning or rearing habitat (Sheer and Steel 2006) and can result in the absence of local populations (Hanrahan et al. 2004, Sheer and Steel 2006).

Considerable work has been done to assess fish passage and to alter migration barriers to restore natural movement patterns and to provide access to spawning, rearing, and overwintering habitats (Clarkin et al. 2005, Price et al. 2010). Considerable work also has been done to evaluate factors influencing downstream emigration

of smolt (Kemp et al. 2005, 2009, Gessel and Williams 2009). However, very little work has been done to assess the effects of migration barriers on Pacific salmon juveniles during their freshwater residency. Rearing anadromous fish migrate from spawning areas and among freshwater rearing locations in search of food resources, in response to antagonistic behavior, or to avoid extreme environmental conditions and physical habitat characteristics (Quinn 2005). Juvenile salmon require access to rearing or overwintering habitats that are often considerable distances from spawning areas (Carlson 1992, Carlson and Hasbrouck 1993, Murphy et al. 1997). Therefore, blocking or limiting access to these areas may affect the distribution and fitness of rearing salmon. However, only a portion of the juvenile salmon population migrates (Quinn 2005), and because of seasonal changes in water velocity, fish size, and swimming ability, only some migrating juveniles are deterred by crossing structures. Larger, older fish may be able to navigate an obstacle that smaller, younger fish cannot. Thus, the effects of potential migration barriers on rearing juvenile salmon distribution are uncertain.

Assessment of barriers to migration by juvenile salmon often is based on culvert modification to channel

¹ E-mail address: arri@mtaonline.net

physical characteristics, including width, slope, and substrate (Flanders and Cariello 2000, Rich 2003, Gibson et al. 2005). However, channel constriction or increasing slopes at a crossing location may not always result in flow velocities that exceed fish swimming ability. Potential migration barriers also can be assessed by comparing fish swimming speeds measured in laboratories to modeled flow velocities at crossings (Behlke et al. 1991; FishXing, version 3, available from: <http://www.stream.fs.fed.us/fishxing>). This approach also has limitations. Modeled flow velocities may be inaccurate (Davis and Davis 2008), and models cannot account for slow velocities and eddies within the substrate used by juvenile Pacific salmon as refugia and resting areas. Moreover, the ability of fish to swim in the laboratory may not reflect their ability in the stream (Haro et al. 2004, Peake 2004).

Site-specific assessment of fish passages based on stream physical characteristics, models, and laboratory swimming ability cannot provide a complete picture of the effects of barriers on the distribution of rearing juvenile salmon. Productive salmon populations can exist above falls or other natural barriers to juvenile migration if these barriers can be negotiated by spawning adults. Similarly, barriers to juvenile migration at road crossings may not affect their distribution if upstream spawning and rearing habitat is accessible to adults and adults can spawn upstream of the juvenile migration barrier.

Considerable work is being done in Alaska to restore fish passage by altering crossing structures to mimic natural stream physical characteristics (W. Rice, US Fish and Wildlife Service, personal communication). However, the number of structures that are potential barriers to migration probably exceeds the funding and time available to devote to these efforts (Smith and Anderson 2008). Thus, stream crossings that reduce or eliminate fish production should be a priority when selecting projects for reconstruction. Reconstruction should restore fish passage and allow natural patterns of juvenile migration. Thus, we must increase our understanding of how crossing structures affect fish passage and of the influence of these barriers on fish distribution and production so that measures of juvenile salmon distribution can be incorporated into assessment and prioritization protocols.

Some investigators have studied fish passage at crossings by comparing movements of marked fish among sites with and without crossing structures (Warren and Pardew 1998, Benton et al. 2008) or by comparing movements of tagged fish prior to and following culvert replacement (M. King, Alaska Department of Fish and Game, unpublished data). However, these methods also do not identify those

sites where migration barriers alter the relative abundance of rearing juvenile fish, i.e., a barrier will influence the distribution of fish only when a portion of the population is attempting to migrate. Minnow trapping often is used to sample juvenile Pacific salmon populations (Bryant 2000). Sampling efficiency of minnow traps can vary among sites, but they are relatively easy to deploy and retrieve and can provide a rapid semiquantitative means to assess differences in relative fish abundance above and below crossings.

We used this method to assess fish passage biologically. Our 1st objective was to determine whether crossing structures identified as potential migration barriers based on changes to channel physical characteristics actually changed the relative abundance of rearing juvenile salmon above and below the crossings. A 2nd objective was to use differences in juvenile salmon catch-per-unit-trap (CPUT) to identify physical characteristics that inhibited fish movement.

Methods

Sampling sites

We worked in south-central Alaska on streams in the Susitna and Little Susitna River drainages (Fig. 1). We selected sampling sites at crossings on 2 stream types ($n = 5$ for each). Upland streams (slope $>1\%$) drained a mixed birch (*Betula* sp.)–spruce (*Picea glauca*) forest, and wetland streams (slope $<1\%$) drained closed black spruce (*Picea mariana*) forests and bluejoint (*Calamagrostis canadensis*) meadows. We chose these 2 stream types because they represent extremes in spawning habitat and stream physical characteristics. Wetland streams were unlikely to provide spawning habitat upstream of crossings, so the upstream presence of juvenile salmon would indicate migration through the crossing. Upland streams provided spawning habitat upstream of crossings, so juvenile abundance probably would decrease if downstream emigration exceeded upstream immigration. These 2 stream types also differed in the physical characteristics used to identify migration barriers. The moderate-slope, upland sites were on streams cataloged by the Alaska Department of Fish and Game (ADFG) as spawning and rearing habitat for coho salmon (*Oncorhynchus kisutch*) or as streams in which spawning coho salmon had been observed. The low-slope, wetland sites were on streams identified as important for rearing of coho salmon where salmon spawning had not been observed and spawning habitat was limited by fine sediments. We selected stream crossings from those identified by the ADFG as barriers or potential

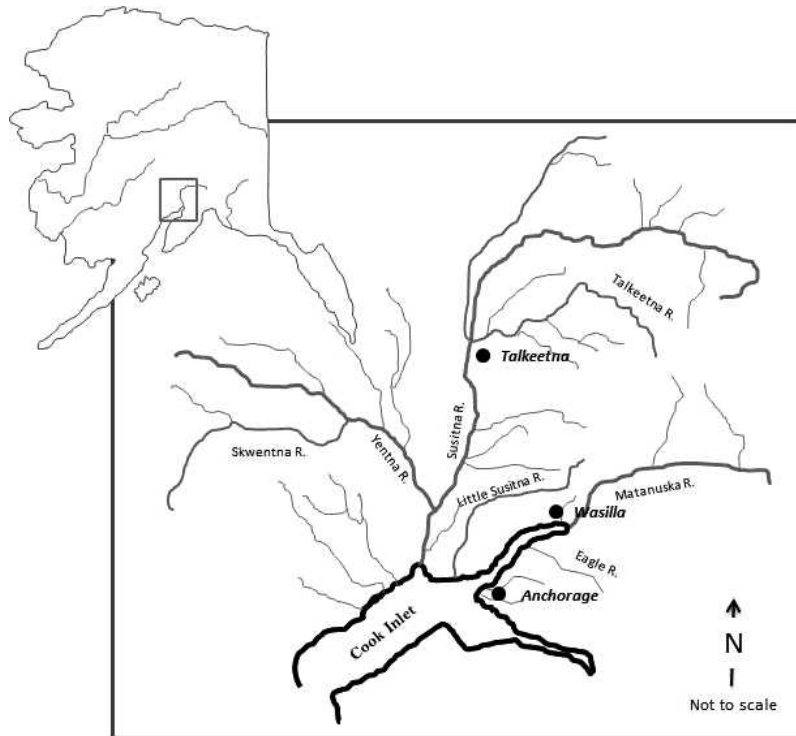


FIG. 1. Drawing of Alaska with inset of the Cook Inlet Region of south-central Alaska.

barriers to juvenile salmon migration (Rich 2003; ADFG Fish Passage Inventory, <http://www.adfg.alaska.gov/index.cfm?adfg=fishpassage.mapping>) based on channel constriction, increased slope, or perched outlet.

We sampled in spring (late May and early June) and autumn (late September) 2008. We sampled in the spring to capture young-of-the-year juvenile salmon newly emerged from spawning redds and juveniles that probably had overwintered in these streams. We sampled in autumn to capture juveniles after migration from spawning locations and after 2 to 3 mo of freshwater rearing. Crossing structures were replaced at Colter Creek and Coles Road between spring and autumn sampling. We extended sampling at these 2 sites into summer (July) 2009.

Physical characteristics

We measured channel width, slope, and substrate particle size above and below crossing structures in reaches close to the crossing to estimate probable natural channel characteristics before road construction. We chose reaches above or below any obvious channel modifications caused by the crossing (i.e., outlet pools, road fill, or constructed channels). Most reaches were $< \sim 20$ m from the culvert inlet or outlet. We measured channel widths on straight channel

sections at ordinary high water (vegetation line) along 5 upstream and 5 downstream transects separated longitudinally by ~ 3 channel widths. We measured water surface and bed slope with a laser level and leveling rod. We calculated slope based on the difference in bed and water-surface heights and the distance between consecutive riffles. We assessed substrate particle size in each reach and culvert qualitatively as silt/sand (< 2 mm), gravel (2–64 mm), cobble (64–256 mm), or boulder (> 256 mm). We measured maximum culvert width and culvert width at the rust line and used a laser level and leveling rod to determine culvert slope from pipe length and the difference between inlet and outlet height. Culvert perch height was the difference in water-surface height between the culvert outlet and outlet pool.

Discharge and water velocity

We measured stream discharge on each sampling date as the sum of component flows with a minimum of 10 flow-velocity measurements (Rantz et al. 1982) taken at $0.6 \times$ depth with a Swoffer velocity meter (Model 3000; Swoffer Instruments, Inc., Seattle, Washington). We measured flow velocity at 3 locations across the culvert inlet and outlet (0.25 , 0.50 , and $0.75 \times$ width) with a Price AA pygmy (Model

1205 Mini meter, Scientific Instruments, Inc., Milwaukee, Wisconsin) or Swoffer meter. We measured water velocity in the culvert with the Price or Swoffer meter if the pipe was tall enough to use the top-set rod (~1.5 m) or with a General Oceanics flow meter (Model 2030, General Oceanics, Inc., Miami, Florida) suspended from the end of a leveling rod extended into the culvert inlet 3 to 4 m. We tested velocity meters for accuracy following manufacturer guidelines prior to use. Juvenile fish are presumed to be able to select low-velocity areas for movement, so we report the lowest of the 3 velocity measurements taken at each site and used this velocity to assess fish passage.

We also measured water velocity based on the flow time of dissolved solutes to define low-velocity regions created by the substrate and available to juvenile fish. We dissolved MgCl in ~15 L of stream water and added the solution as a bolus at the culvert inlet. We measured specific conductance at the culvert outlet. Maximum flow-time velocity was the time at which specific conductance began to increase at the culvert outlet, mean flow-time velocity was the time to peak specific conductance, and minimum flow-time velocity was the time for specific conductance to return to preinjection level divided by the distance between the inlet and outlet.

Juvenile fish passage

We compared water velocities at the crossing to the burst and sustained swimming speeds of juvenile coho salmon. Sustained and burst swimming speeds were taken from equations used in the FishXing program. We calculated sustained and burst swimming speeds as:

$$V_{sustained} = 3.02L^{0.52}t^{-0.1} \text{ and}$$

$$V_{burst} = 13.3L^{0.52}t^{-0.65}$$

where V is velocity (m/s), L is total length (m) (total length = $1.01 \times$ fork length), and t is swimming time (s) with a sustained swimming time of 1800 s and burst swimming time of 10 s. Sustained swimming speed is 0.30 to 0.39 m/s and burst swimming speed is 0.63 to 0.81 m/s for juvenile coho that are 50 to 80 mm fork length.

We evaluated fish passage biologically by sampling the fish assemblage above and below crossings. We used 20 baited (salmon roe) minnow traps (Gee minnow traps, 2.54-cm openings, 6.4-mm mesh; Memphis Net and Twine, Memphis, Tennessee), 10 above and 10 below the crossing, fished for 20 to 24 h. We placed traps in pools or low-velocity areas with

cover provided by deep water, woody debris, or undercut banks. Minnow traps can be size and species selective (Jackson and Harvey 1997, Lapointe et al. 2006), and trap efficiency can vary because of water temperatures (Stott 1970) and fishing time (Culp and Glozier 1989). However, minnow trapping is effective for monitoring relative abundance of some species (He and Lodge 1990, MacRae and Jackson 2006). Rearing juvenile salmon generally are <100-mm fork length and, therefore, should not be affected by size selectivity. We trapped above and below crossings on the same date and left traps in place for the same amount of time to minimize variability in trapping efficiency caused by differences in water temperature, season, flow conditions, or trapping time. We identified all captured fish to species and measured fork length. We assessed each trap individually ($n = 10$ replicate CPUT values per location).

Culvert replacement

Physical characteristics, water velocity, and relative fish abundance were evaluated at 2 crossing locations before and after culvert replacement. The culverts at the Coles Road (unnamed stream) and Sitze Road (Colter Creek) crossings were replaced by the US Fish and Wildlife Service to improve fish passage. Corrugated metal pipe culverts were replaced with bottomless arch culverts. The new culverts were designed to replicate natural channel widths, slopes, and substrate. Differences in CPUT above and below the culvert, stream and culvert physical characteristics, discharge, and water velocity were measured before and after culvert replacement.

Statistical tests

We used paired t -tests ($\alpha = 0.05$) to test for differences in upstream and downstream mean CPUT because CPUT in each stream was independent. Mean CPUT downstream of a road culvert could vary considerably among streams and could not be considered as coming from the same statistical population. That is, we were not testing whether mean CPUT below all crossings was different from CPUT above all crossings, but whether CPUT differed significantly above and below road crossings within streams. We tested for differences between above- and below-crossing CPUT in spring wetland ($n = 5$), autumn wetland ($n = 5$), spring upland ($n = 5$), autumn upland ($n = 4$), combined spring and autumn wetland ($n = 10$), and combined spring and autumn upland ($n = 9$) streams independently. We compared mean CPUT for total juvenile coho, coho ≤ 55 mm fork length (approximate length of age-0 fish), coho

>55 mm fork length (approximate length of age-1 fish), Chinook salmon (*Oncorhynchus tshawytscha*), resident rainbow trout (*Oncorhynchus mykiss*), and resident Dolly Varden char (*Salvelinus malma*). We used paired *t*-tests ($\alpha = 0.05$) to test for differences in CPUT above and below Coles Road and above and below Colter Creek crossings independently prior to and following site restoration. Pearson correlation was used to evaluate relationships among channel and crossing physical characteristics, maximum culvert velocities, and differences in juvenile salmon CPUT between upstream and downstream samples.

Results

Fish passage in upland and wetland streams

Juvenile coho salmon were the dominant salmonid species captured. Juvenile Chinook salmon and resident Dolly Varden char and rainbow trout were present but in lower numbers. Chinook salmon were captured in both stream types during autumn but were not present in upland streams in spring. Chinook salmon made up 0.5% of total CPUT in wetland streams and 2.8% of total CPUT in upland streams (upstream and downstream data combined). Rainbow trout were found in upland and wetland streams, but Dolly Varden char were not caught in wetland streams (Table 1). Resident fish were 1.8% of total average CPUT in wetland streams and 34% of total average CPUT in upland streams (upstream and downstream data combined).

Upland streams.—CPUT of juvenile coho (total coho, coho ≤ 55 mm, coho > 55 mm) salmon was significantly higher in autumn than in spring (total coho: $p = 0.01$; coho ≤ 55 mm: $p = 0.05$; coho > 55 mm: $p = 0.03$). Chinook salmon were absent from spring samples, but mean CPUT above and below the crossing (combined) increased to 0.8 ± 0.14 in autumn. CPUT for resident fish (total, rainbow trout, Dolly Varden char) did not differ between spring and autumn (all $p > 0.05$).

When all sampling dates were included, juvenile coho CPUT was significantly higher above than below crossings (total coho: $t = 3.19$, $p < 0.006$; coho ≤ 55 mm: $t = 2.06$, $p = 0.04$; coho > 55 mm: $t = 3.32$, $p = 0.005$). CPUT for Chinook salmon and resident fish did not differ above and below crossings (all $p > 0.05$; data not shown). In spring, CPUT for juvenile coho and resident fish did not differ above and below crossings (all $p > 0.05$). In autumn, CPUT for juvenile coho was significantly higher above than below crossings (total coho: $t = 6.24$, $p < 0.004$; coho ≤ 55 mm: $t = 2.15$, $p = 0.05$; coho > 55 mm: $t = 3.87$, $p = 0.02$), but CPUT for Chinook salmon and resident

TABLE 1. Mean (SD; $n = 10$) catch-per-unit-trap (CPUT) above and below road-crossing culverts in upland and wetland streams during spring and autumn sampling. UP = upstream of crossing, DN = downstream of crossing, \leq and > 55 refer to fork length (mm) of juvenile salmon. * denotes significant difference between upstream and downstream CPUT ($p < 0.05$).

Stream type	Total coho salmon			Coho salmon ≤ 55			Coho salmon > 55			Chinook salmon			Dolly Varden			Rainbow trout		
	UP	DN		UP	DN		UP	DN		UP	DN		UP	DN		UP	DN	
Upland																		
Spring	4.7 (3.8)	2.9 (2.4)		2.1 (2.0)	1.6 (1.8)		2.7 (2.1)	1.3 (0.9)		0.00	0.0		1.7 (1.6)	2.0 (2.1)		0.38 (0.80)	0.7 (1.7)	
Autumn	12.5 (4.6)*	6.2 (4.0)		6.1 (4.4)*	3.3 (3.0)		6.4 (3.1)*	2.9 (1.5)		0.5 (1.0)	1.1 (1.3)		2.3 (3.3)	2.7 (3.6)		0.93 (1.9)	1.5 (3.1)	
Combined	8.2 (5.6)*	4.3 (3.5)		3.9 (3.7)*	2.4 (2.4)		4.3 (3.1)*	2.0 (1.4)		0.2 (0.7)	1.0 (0.5)		1.9 (2.3)	2.3 (2.7)		0.62 (1.3)	1.1 (2.2)	
Wetland																		
Spring	1.1 (1.2)	4.0 (3.2)		0.1 (0.2)	0.3 (0.4)		1.0 (1.1)	3.7 (3.0)		0.02 (0.04)	0.0		0.0	0.0		0.0	0.19 (0.3)	
Autumn	5.9 (6.3)	17.2 (19.0)		1.1 (1.7)	6.5 (8.5)		4.8 (4.7)	10.7 (10.6)		0.02 (0.04)	0.2 (0.3)		0.0	0.0		0.04 (0.05)	0.18 (0.3)	
Combined	3.5 (5.0)	10.6 (14.6)		0.6 (1.3)	3.4 (6.6)		2.9 (3.7)	7.2 (8.2)		0.02 (0.04)	0.1 (0.2)		0.0	0.0		0.02 (0.04)	0.19 (0.3)*	

fish did not differ above and below crossings (all $p > 0.05$).

Wetland streams.—CPUT for juvenile coho and resident fish did not differ significantly between spring and autumn (all $p > 0.05$), but mean total coho CPUT increased from 2.6 ± 1.9 in spring to 11.5 ± 10.4 in autumn. In spring, CPUT for juvenile coho did not differ above and below crossings (all $p > 0.05$). In autumn, CPUT of juvenile coho tended to be higher below than above crossings, but the differences were not statistically significant (upstream CPUT of total coho = 5.9 ± 6.3 , downstream CPUT of total coho = 17.2 ± 19.0). Using combined spring and autumn samples, CPUT of resident rainbow trout was significantly higher downstream than upstream of crossings (upstream CPUT = 0.02 ± 0.04 , downstream CPUT = 0.19 ± 0.3 ; $t = 1.94$, $p = 0.04$).

Physical characteristics

Upland streams.—Physical characteristics of culverts and upland channels differed. Culverts were 0.30 to $0.76\times$ narrower than mean channel widths (Table 2). Culvert slopes were steeper than upstream channel slopes at all crossings, and were steeper than downstream channel slopes at 3 of the 5 crossings (Table 2). Maximum culvert velocity was negatively correlated with the ratio of culvert width to stream width (upstream ratio: $r = -0.88$) and positively correlated with culvert slope ($r = 0.82$) (Table 3). Maximum culvert velocity was not correlated with the ratio of culvert to stream slope ($r = -0.19$). The difference in total coho salmon CPUT (CPUT above crossing – CPUT below crossing) was negatively correlated with the ratio of culvert to channel width ($r = -0.97$, $p = 0.005$).

Wetland streams.—Physical characteristics of wetland channels and culverts also differed. Culverts were 0.3 to $0.7\times$ narrower than channel widths except at 1 crossing where the combined width of 2 culverts approximated stream channel width (Table 2). Culvert slopes were 2 to $10\times$ steeper than upstream and downstream channel slopes except at 2 crossings where culvert slopes were less than upstream channel slopes, and one crossing where culvert slope was less than upstream and downstream channel slope (Table 2). Culverts at Mile 107.6, Mile 118.7, and Greys Creek were perched (Table 2). CPUT of juvenile coho and resident fish differed above and below the Mile 107.6 and Greys Creek crossings (heights = 1.33 and 0.18 m; both $p < 0.05$). In both seasons, the upstream–downstream difference in CPUT of juvenile coho was not correlated with maximum velocity or the ratios of culvert to channel widths or slopes (all $p > 0.05$) but

was correlated with culvert perch height (spring: $r = 0.90$, $p = 0.04$; autumn: $r = 0.98$, $p = 0.003$) (Table 4).

Discharge and water velocity

Juvenile coho CPUT differed above and below crossings where maximum flow velocities exceeded burst swimming speeds or minimum flow-time velocities exceeded the sustained swimming speeds of juvenile coho salmon (Fig. 2). Using a burst swimming speed of 0.70 m/s and a sustained swimming speed of 0.30 m/s, all but 3 crossings would be barriers to fish migration during low-flow conditions in the spring based on maximum water velocities measured at the culvert inlet, outlet, and middle or by the flow time of dissolved solutes. During higher autumn discharge, water velocity in the culverts exceeded juvenile salmon sustained swimming speeds at all crossings measured except in 2 wetland streams.

Culvert replacement

Replacement of the Colter Creek and Coles Road crossings restored natural channel widths, slopes, and substrate; reduced water velocities (Table 5); and eliminated upstream–downstream differences in juvenile coho CPUT (Table 6). The Colter Creek crossing was reconstructed in September 2008. Maximum velocities still exceeded burst swimming speeds and minimum flow-time velocities exceeded the sustained swimming speeds of juvenile coho salmon shortly after reconstruction during high autumn discharge ($0.40 \text{ m}^3/\text{s}$). However, by mid-July 2009, stream flows had decreased to $0.05 \text{ m}^3/\text{s}$, and maximum and minimum water velocities in the culvert were well below the burst and sustained swimming speeds of juvenile coho salmon. Juvenile coho CPUT was higher above than below the Colter Creek crossing prior to and immediately after reconstruction in September 2008 ($t = 2.93$, $p = 0.008$), but did not differ above and below the crossing in spring or autumn of 2009 (both $p > 0.05$; Table 6).

The Coles Road crossing was reconstructed in August 2008. In September 2008 during higher flows ($0.14 \text{ m}^3/\text{s}$), water velocities were lower than pre-restoration values (Table 5). Maximum velocities were below the burst swimming speeds and minimum velocities were below sustained swimming speeds of 55-mm juvenile coho. During July 2009, stream discharge was near $0.04 \text{ m}^3/\text{s}$ and maximum and minimum water velocities were <0.54 and 0.23 m/s , respectively. Prior to reconstruction, CPUT of total coho, coho $\leq 55 \text{ mm}$, and coho $>55 \text{ mm}$ were significantly higher upstream of the crossing (total

TABLE 2. Mean stream channel and culvert physical characteristics upstream (UP) and downstream (DN) of culverts or in culverts at upland and wetland stream crossings. For sites with multiple culverts, only 1 value for channel characteristics is provided.

Stream	Slope		Culvert slope/ channel slope		Culvert width (m)		Channel width (m)		Culvert width/ channel width		Culvert substrate	Perch height (m)	
	Culvert	UP	DN	UP	DN	UP	DN	UP	DN	UP			DN
	Upland												
Answer Creek	0.014	0.005	0.016	2.80	0.88	3.32	3.18	4.98	5.94	0.67	0.54	None	
Sunrise Creek	0.028	0.017	0.035	1.65	0.80	2.66	2.76	3.50	4.00	0.76	0.69	None	
Coles Road	0.045	0.013	0.035	3.46	1.29	1.24	1.16	2.59	2.04	0.48	0.57	None	
Colter Creek	0.050	0.009	0.043	5.56	1.16	1.50	1.50	3.48	4.08	0.43	0.37	None	
Russett Creek	0.040	0.001	0.010	40.00	4.00	1.19	1.22	1.80	1.89	0.66	0.65	None	
Wetland													
Mile 107.6	0.040	0.072	0.015	0.56	2.67	1.20	1.22	2.99	2.55	0.40	0.48	None	
Mile 118.7	0.005	0.037	0.016	0.14	0.31	1.83	1.83	4.83	5.23	0.38	0.35	Cobble	
Upper Rabideux	0.020	0.007	0.001	2.86	20.00	4.40	4.40	4.06	4.52	1.08	0.97	Gravel	
Sawmill Creek	0.039	0.004	0.031	10.00	1.26	2.32	2.35	7.02	5.64	0.33	0.42	Boulders	
Greys Creek	0.008	0.002	0.003	4.00	2.67	2.90	2.90	4.26	4.16	0.68	0.70	Boulders	

TABLE 3. Correlation coefficients for upland stream crossings showing relationship between juvenile coho salmon abundance and culvert width/stream widths. Spring and autumn coho difference is the difference in CPUT above and below a road crossing. UP = upstream, DN = downstream, ND = no data.

Variable	Coho difference				Slope				Width				Culvert width/ stream width				Culvert slope/ stream slope	Perch height	Maximum velocity		
	Spring	Autumn	Culvert	Channel	Channel	Channel	Culvert	Channel	Channel	Channel	UP	DN	UP	DN	UP	DN				UP	DN
	Spring coho difference	1.00																			
Autumn coho difference	0.97	1.00																			
Culvert slope	0.57	0.40	1.00																		
Channel slope UP	-0.21	0.99	0.08	1.00																	
Channel slope DN	0.44	0.98	0.50	0.78	1.00																
Channel width UP (m)	0.08	0.40	-0.70	0.13	0.09	1.00															
Channel width DN (m)	0.00	-0.01	-0.81	-0.32	-0.38	0.87	1.00														
Channel width DN (m)	0.09	0.41	-0.71	0.03	0.02	0.98	0.87	1.00													
Culvert width/stream width UP	-0.88	-0.92	-0.74	0.01	-0.53	0.16	0.25	0.24	1.00												
Culvert width/stream width DN	-0.97	-1.00	-0.38	0.16	-0.45	-0.31	-0.20	-0.31	-0.31	1.00											
Culvert slope/stream slope UP	-0.13	-0.74	0.24	-0.73	-0.67	-0.70	-0.32	-0.58	-0.58	0.17	0.30	1.00									
Culvert slope/stream slope DN	-0.12	-0.73	0.30	-0.71	-0.65	-0.76	-0.38	-0.65	-0.65	0.11	0.30	0.99	1.00								
Perch height (m)	-0.63	ND	-0.29	0.71	0.29	0.11	-0.20	0.14	0.14	0.65	0.58	-0.31	-0.34	1.00							
Maximum velocity (m/s)	0.92	0.81	0.82	0.46	0.85	-0.21	-0.54	-0.18	-0.18	-0.88	-0.77	-0.20	-0.19	ND							

TABLE 4. Correlation coefficient for wetland stream crossings showing relationship between culvert perch height and relative juvenile coho salmon abundance. UP = upstream, DN = downstream, ND = no data.

Variable	Coho difference		Slope		Channel		Width		Culvert width/ stream width		Culvert slope/ stream slope		Perch height	Maximum velocity
	Spring	Autumn	Culvert	Channel UP	Channel DN	Channel UP	Culvert DN	Channel DN	UP	DN	UP	DN		
Spring coho difference	1.00													
Autumn coho difference	0.90	1.00												
Culvert slope	0.37	0.58	1.00											
Channel slope UP	0.66	0.85	0.32	1.00										
Channel slope DN	-0.14	0.02	0.57	0.14	1.00									
Channel width UP (m)	-0.67	-0.65	0.14	-0.59	0.71	1.00								
Culvert width DN (m)	-0.42	-0.74	-0.44	-0.93	-0.24	0.44	1.00							
Channel width DN (m)	-0.93	-0.91	-0.29	-0.69	0.38	0.87	0.51	1.00						
Culvert width/stream width UP	-0.22	-0.25	-0.31	-0.44	-0.82	-0.35	0.36	1.00						
Culvert width/stream width DN	-0.11	-0.17	-0.19	-0.45	-0.79	-0.35	0.38	-0.07	1.00					
Culvert slope/stream slope UP	-0.35	-0.41	0.41	-0.66	0.54	0.84	0.55	-0.15	-0.14	1.00				
Culvert slope/stream slope DN	-0.28	-0.15	-0.04	-0.30	-0.61	-0.28	0.10	0.05	0.93	0.90	1.00			
Perch height (m)	0.90	0.98	0.47	0.91	0.04	-0.66	-0.77	-0.89	-0.35	-0.29	-0.51	1.00		
Maximum velocity (m/s)	0.54	0.33	-0.56	0.42	-0.58	-0.74	-0.12	-0.57	0.01	-0.02	-0.78	-0.24	0.44	1.00

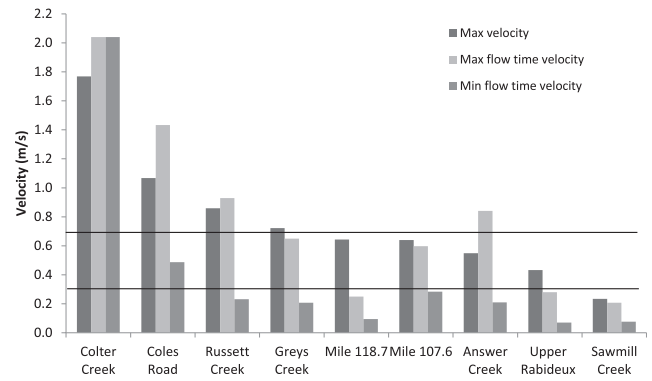


FIG. 2. Culvert water velocities under low-flow conditions. Solid lines correspond to burst and sustained swimming speeds of 55-mm coho salmon. Sunrise Creek data are not included because of a velocity meter malfunction. Max = maximum, min = minimum.

coho: $t = 2.01, p = 0.04$; coho ≤ 55 mm: $t = 1.76, p = 0.05$; coho > 55 mm: $t = 2.11, p = 0.03$). CPUT of juvenile coho did not differ above and below the crossing on either post reconstruction sampling date (both $p > 0.05$; Table 6).

Discussion

Our results support the hypothesis that stream-crossing structures (culverts) can alter the distribution of juvenile salmon resulting in upstream-downstream differences in relative abundance. The effects of culverts on juvenile CPUT appeared to be dependent on the location of adult spawning habitat. In upland streams, where spawning occurred upstream of the culvert, juvenile CPUT generally was greater upstream than downstream of the culverts. Thus, downstream migration of juvenile coho appeared to be restricted. In wetland streams, spawning occurred below culverts, and CPUT tended to be lower below than above perched culverts. Thus, culverts appeared to be barriers to migration. Correlations between flow velocities and distribution patterns suggest the possibility that juvenile coho avoided water velocities that exceeded their burst and sustained swimming speeds regardless of whether they were attempting to move up- or downstream. Reconstruction of 2 crossings with bottomless arch pipes that mimicked natural stream channel widths, slopes, and substrate reduced water velocities and eliminated upstream-downstream differences in CPUT of juvenile coho and resident fish.

Upon emergence from spawning gravels, salmon fry migrate upstream or downstream to rearing and overwintering locations (Kahler and Quinn 1998). In the upland streams in our study, crossing structures

TABLE 5. Stream discharge and culvert water velocities at 2 locations before (pre) and after (post) reconstruction of road crossings.

Variable	Colter Creek			Coles Road		
	Pre 6/13/2007	Post 9/25/2008	Post 7/27/2009	Pre 7/20/2008	Post 9/26/2008	Post 7/28/2009
Discharge (m ³ /s)	0.14	0.40	0.05	0.06	0.14	0.04
Culvert inlet (m/s)	1.77	0.65	0.27	0.55	0.82	0.12
Culvert middle (m/s)	2.39	NM	0.15	0.00	0.00	0.11
Culvert outlet (m/s)	1.39	0.88	0.16	1.07	0.36	0.20
Maximum flow time (m/s)	2.04	0.88	0.44	1.43	0.87	0.54
Minimum flow time (m/s)	2.04	0.40	0.21	0.49	0.29	0.23
Average flow time (m/s)	2.04	0.73	0.31	0.97	0.62	0.39

were not barriers to migration of adult coho salmon. Adult salmon or salmon carcasses were observed upstream of all crossings except the Sunrise Road crossing. Juvenile coho salmon can migrate out of tributary streams during autumn storms (Quinn 2005), and we anticipated that a portion of the emerging fry would migrate downstream across the migration barrier, decreasing upstream abundance. We expected that age-0 fish emigrating from tributary streams across a migration barrier would be unable to return for their 2nd year of freshwater residency and that upstream abundance of rearing salmon would decrease as a consequence. We did find higher CPUT of resident rainbow trout and Dolly Varden below than above culverts. However, counter to our expectation, we also found higher CPUT of juvenile coho above than below culverts. Previous studies have shown that migrating Chinook salmon smolt avoid areas of high flow velocity as they migrate downstream (Kemp et al. 2005) and that culverts can limit downstream migration of juvenile salmon (M. King, unpublished data). Results from our study support

the hypothesis that juvenile coho salmon avoid the high flow velocities encountered at culvert inlets resulting in increased upstream abundance. Crossing structures that generate high velocity conditions may be analogous to waterfalls or other small barriers near salt water that do not limit adult salmon access to spawning habitat but are barriers to juvenile migration. Salmon fry that emigrate from these streams upon emergence may have decreased survival. Thus, avoidance of high-flow areas might be an adaptive response.

The presence of rearing juvenile salmon in spring samples indicates that a portion of the population overwintered successfully in these small upland tributary streams. These 1st- or 2nd-order tributary streams usually are ice-covered in October and do not become ice-free until May. The amount of flowing surface water is very limited, and overwintering habitat may be restricted to interstitial or subsurface flows. Overwintering within the substrate is a survival mechanism for rearing juvenile trout (Smith and Griffith 1994). The Sitze Road crossing of Colter

TABLE 6. Fish catch-per-unit-trap above and below crossing structures before (pre) and after (post) site restoration at Colter Creek and Coles Road. CO = coho salmon, K = Chinook (King) salmon, DV = Dolly Varden char, ≤ 55 or >55 = fork length (mm), and TOT = total juvenile salmonids. * denotes significant difference from before to after restoration ($p < 0.05$).

Variable	Colter Creek				Coles Road		
	Pre 6/3/2008	Post 9/25/2008	Post 5/26/2009	Post 7/27/2009	Pre 6/4/2008	Post 9/23/2008	Post 7/28/2009
UPCO	9.9*	11.9*	0.3	5.9	3.6*	4.2	1.5
DNCO	3.4	3.2	0.7	5.8	0.7	3.5	2.1
UPCO ≤ 55	3.9	7.8*	0.1	1.0	2.2*	3.6	0.5
DNCO ≤ 55	1.5	2.1	0.4	1.9	0.6	3.3	1.2
UPCO >55	6.0*	4.1*	0.2	4.9	1.4*	0.6	1.0
DNCO >55	1.9	1.1	0.3	3.9	0.1	0.2	0.9
UPK	0.0	2.0	0.0	1.2	0.0	0.0	0.0
DNK	0.0	2.6	0.0	2.3	0.0	0.0	0.0
UPDV	2.3	1.8	1.6	3.6	3.0	1.9	3.9
DNDV	1.8	1.1	0.7	3.3	1.9	2.6	4.6
UPTOT	12.2*	15.7*	1.9	10.7	6.6*	6.1	5.4
DNTOT	5.2	6.8	1.4	11.4	2.6	6.1	6.7

Creek was a barrier to juvenile fish migration (flow velocities >1.8 m/s). However, spring CPUT of (presumably) age-1 fish was higher above than below the crossing. Therefore, winter survival in these small streams clearly is possible.

We did not find significant differences in rearing juvenile salmon above and below wetland stream crossing, even though juveniles were absent upstream of some road crossings. Sites were selected as potential barriers based upon assessment methods used by the Alaska Department of Fish and Game that are based on modification of stream channel widths and slopes. Channel constriction and increases in channel slopes in wetland streams did not result in higher water velocities or differences in abundance of rearing juvenile salmon. Differences in coho abundance in wetland streams were related to culvert perch heights. Therefore, some of the crossings at wetland streams blocked juvenile salmon migration and some probably did not. Culverts that are migration barriers to juvenile coho can result in nearly complete absence of salmon upstream of the crossing. Many low-slope wetland streams contain sediment deposits of fine silts and sands. These substrates do not provide quality spawning habitat, so rearing salmon distribution into wetland streams is largely the result of juvenile immigration. The crossing at Mile 107.6, with a perch height >1 m, is a clear barrier to migration of juvenile salmon. This stream is a tributary to Rabideux Creek, which supports coho and Chinook salmon spawning. CPUT was 10 to 40 juvenile coho salmon greater downstream than upstream of the barrier. This difference is the equivalent of 100 to 400 fish/100-m sampling reach or a total of 5000 to 20,000 fish (if one can extrapolate to the entire 5 km of stream isolated by this crossing). CPUT represents only a portion of the total population, so these values underestimate of the effect of this crossing on rearing salmon.

Our results support our previous findings (Davis and Davis 2008) that measures of channel modification at crossing locations alone are not adequate to evaluate potential migration barriers. Channel constriction at crossing locations was related to maximum culvert velocities in upland but not wetland streams. Therefore, assessing fish passage based on changes in physical characteristics at all locations may overestimate the effect of culverts. A combination of measures of CPUT, channel and culvert physical characteristics, point measures of flow velocity, and flow-time measures of water velocity were most effective tools for evaluating culverts as potential barriers. Point measures of flow velocity at the culvert inlet and outlet are necessary to document areas

where flow velocity is likely to exceed burst swimming speeds of migrating fish. Flow time of dissolved solutes takes into account the effects of transient storage areas (Webster and Valett 2006), which may be related to availability of low-velocity areas that could be used by 55-mm-long juvenile salmon. However, we did not study this relationship quantitatively. Water velocities within or adjacent to the substrate are slower and more descriptive of velocities experienced by juvenile salmon than mean vertical velocities measured at $0.6 \times$ depth.

Stream crossings can influence the distribution of rearing juvenile salmon. Our findings suggest that culverts can increase or decrease fish abundance depending on the placement of the barrier in the watershed. Changes in abundance of juvenile salmon may influence their fitness and survival via intraspecific interactions including competition for space and resources (Chapman 1966, Walters and Juanes 1993, Imre et al. 2005) and could affect the trophic structure of the stream ecosystem (Cooper et al. 1990, Polis et al. 1997).

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Literature Cited

- BEHLKE, C., D. KANE, R. F. MCLEAN, AND M. D. TRAVIS. 1991. Fundamentals of culvert design for passage of weak-swimming fish. FHWA-AK-RD-90-10: 1-203. Alaska Department of Transportation and Public Facilities, Fairbanks, Alaska. (Available from: Alaska Department of Transportation and Public Facilities, 2301 Peger Road, Fairbanks, Alaska 99709 USA.)
- BENTON, P. D., W. E. ENSIGN, AND B. J. FREEMAN. 2008. The effect of road crossings on fish movements in small Etowah Basin streams. *Southeastern Naturalist* 7: 301-310.
- BRYANT, M. D. 2000. Estimating fish population by removal methods with fish traps in Southeast Alaska. *North American Journal of Fisheries Management* 20:923-930.
- CARLSON, J. A. 1992. Feasibility of capturing and marking juvenile coho salmon for stock assessment in the Kenai River. Fishery Data Series No. 92-57. Division of Sport Fish, Alaska Department of Fish and Game, Fairbanks, Alaska. (Available from: Alaska Department of Fish and Game, 333 Raspberry Road, Anchorage, Alaska 99518 USA.)
- CARLSON, J. A., AND J. J. HASBROUCK. 1993. Marking juvenile coho salmon in the Kenai River with coded, microwire tags. Division of Sport Fish, Alaska Department of Fish

- and Game, Fairbanks, Alaska. (Available from: Alaska Department of Fish and Game, 333 Raspberry Road, Anchorage, Alaska 99518 USA.)
- CHAPMAN, D. W. 1966. Food and space as regulators of salmonid populations in streams. *American Naturalist* 100:345–357.
- CLARKIN, K., A. CONNOR, M. J. FURNISS, B. GUBERNICK, M. LOVE, K. MOYNAN, AND S. WILSON MUSSER. 2005. National inventory and assessment procedure for identifying barriers to aquatic organisms passage at road-stream crossings. National Technology and Development Program 7700: Transportation Management. US Department of Agriculture Forest Service, San Dimas, California. (Available from: 444 E. Bonita Ave., San Dimas, California 91773 USA.)
- COOPER, S. D., S. J. WALDE, AND B. L. PECKARSKY. 1990. Prey exchange rates and the impact of predators on prey populations. *Ecology* 71:1503–1514.
- CULP, J. M., AND N. E. GLOZIER. 1989. Experimental evaluation of a minnow trap for small lotic fish. *Hydrobiologia* 175: 83–87.
- DAVIS, J. C., AND G. A. DAVIS. 2008. Restoration evaluation—fish passage. Final report for the US Fish and Wildlife Service. Aquatic Restoration and Research Institute, Talkeetna, Alaska. (Available from: ARRI, P.O. Box 923, Talkeetna, Alaska 99676 USA.)
- FLANDERS, L. S., AND J. CARIELLO. 2000. Tongass road condition survey report. Technical Report 00-7. Alaska Department of Fish and Game, Fairbanks, Alaska. (Available from: Alaska Department of Fish and Game, 333 Raspberry Road, Anchorage, Alaska 99518 USA.)
- GESSEL, M. H., AND J. G. WILLIAMS. 2009. Development of successful fish passage structures for downstream migrants requires knowledge of their behavioral response to accelerating flow. *Canadian Journal of Fisheries and Aquatic Sciences* 66:2109–2117.
- GIBSON, R. J., R. L. HAEDRICH, AND C. M. WERNERHEIM. 2005. Loss of fish habitat as a consequence of inappropriately constructed stream crossings. *Fisheries* 30(1):10–17.
- HANRAHAN, T. P., D. D. DAUBLE, AND D. R. GEIST. 2004. An estimate of Chinook salmon (*Oncorhynchus tshawytscha*) spawning habitat and redd capacity upstream of a migration barrier in the upper Columbia River. *Canadian Journal of Fisheries and Aquatic Sciences* 61:23–33.
- HARO, A., T. CASTRO-SANTOS, J. NOREIKA, AND M. ODEH. 2004. Swimming performance of upstream migrant fishes in open-channel flow: a new approach to predicting passage through barriers. *Canadian Journal of Fisheries and Aquatic Sciences* 61:1590–1601.
- HARO, A., M. ODEH, J. NOREIKA, AND T. CASTRO-SANTOS. 1998. Effect of water acceleration on downstream migratory behavior and passage of Atlantic salmon smolts and juvenile American shad at surface bypasses. *Transactions of the American Fisheries Society* 127:118–127.
- HE, X., AND D. M. LODGE. 1990. Using minnow traps to estimate fish population size: the importance of spatial distribution and relative species abundance. *Hydrobiologia* 190:9–14.
- IMRE, I., J. W. A. GRANT, AND R. A. CUNJAK. 2005. Density-dependent growth of young-of-the-year Atlantic salmon in Catamaran Brook, New Brunswick. *Journal of Animal Ecology* 74:508–516.
- JACKSON, D. A., AND H. H. HARVEY. 1997. Qualitative and quantitative sampling of lake fish communities. *Canadian Journal of Fisheries and Aquatic Sciences* 54: 2807–2813.
- KAHLER, T. H., AND T. P. QUINN. 1998. Juvenile and resident salmonid movement and passage through culverts. Final Research Report, Research Project T9903, Task 96, Salmon thru culvert. Washington State Transportation Center, Seattle, Washington. (Available from: 1107 NE 45th Street, Suite 535, Seattle, Washington 98105-4631 USA.)
- KARLE, K. F. 2005. Analysis of an efficient fish barrier assessment protocol for highway culverts. FHWA-AK-RD-05-02. Statewide Research Office, Alaska Department of Transportation Hydraulic Mapping and Modeling, Statewide Research Office, Denali Park, Alaska. (Available from: Alaska Department of Transportation, 3132 Channel Drive, Juneau, Alaska 99801-7898 USA.)
- KEMP, P. S., M. H. GESSEL, AND J. G. WILLIAMS. 2005. Fine-scale behavioral responses of Pacific salmonid smolts as they encounter divergence and acceleration of flow. *Transactions of the American Fisheries Society* 134:390–398.
- KEMP, P. S., M. H. GESSEL, AND J. G. WILLIAMS. 2009. Response of downstream migrating juvenile Pacific salmonids to accelerating flow and overhead cover. *Hydrobiologia* 609:205–217.
- LAPOINTE, N. W. R., L. D. CORKUM, AND N. E. MANDRAK. 2006. A comparison of methods for sampling fish diversity in shallow offshore waters of large rivers. *North American Journal of Fisheries Management* 26:503–513.
- MACRAE, P. S. D., AND D. A. JACKSON. 2006. Characterizing north temperate lake littoral fish assemblages: a comparison between distance sampling and minnow traps. *Canadian Journal of Fisheries and Aquatic Sciences* 63:558–568.
- MURPHY, M. L., K. V. KOSKI, J. J. LORENZ, AND J. F. THEDINGA. 1997. Downstream migrations of juvenile Pacific salmon (*Oncorhynchus* spp.) in a glacial transboundary river. *Canadian Journal of Fisheries and Aquatic Sciences* 54: 2837–2846.
- PEAKE, S. 2004. An evaluation of the use of critical swimming speed for determination of culvert water velocity criteria for smallmouth bass. *Transactions of the American Fisheries Society* 133:1472–1479.
- POLIS, G. A., W. B. ANDERSON, AND R. D. HOLT. 1997. Toward an integration of landscape and food web ecology: the dynamics of spatially subsidized food webs. *Annual Review of Ecology and Systematics* 28:289–316.
- PRICE, D. M., T. QUINN, AND R. J. BARNARD. 2010. Fish passage effectiveness of recently constructed road crossing culverts in the Puget Sound Region of Washington State. *North American Journal of Fisheries Management* 30:1110–1125.
- QUINN, T. P. 2005. The behavior and ecology of Pacific salmon and trout. University of Washington Press, Seattle, Washington.

- RANTZ, S. E., AND OTHERS. 1982. Measurement and computation of streamflow. Volume 1. Measurement of stage and discharge. U.S. Geological Survey Water-Supply Paper 2175. US Geological Survey, Reston, Virginia.
- RICH, C. F. 2003. Fish passage at culverts on the Kenai Peninsula, Alaska. Draft fishery data report series No. 03-XX. Division of Sport Fish, Alaska Department of Fish and Game, Anchorage, Alaska. (Available from: Alaska Department of Fish and Game, 333 Raspberry Road, Anchorage, Alaska 99518 USA.)
- SCHAEFER, J. F., E. MARSH-MATTHEWS, D. E. SPOONER, K. B. GIDO, AND W. J. MATTHEWS. 2003. Effects of barriers and thermal refugia on local movement of the threatened Leopard Darter, *Percina pantherina*. *Environmental Biology of Fishes* 66:391–400.
- SHEER, M. B., AND E. A. STEEL. 2006. Lost watersheds: barriers, aquatic habitat connectivity, and salmon persistence in the Willamette and Lower Columbia River Basins. *Transactions of the American Fisheries Society* 135: 1654–1669.
- SMITH, C., AND J. ANDERSON. 2008. Conserving salmon habitat in the Mat-Su Basin—The strategic action plan of the Mat-Su Basin salmon habitat partnership. (Available from: The Nature Conservancy, 715 L Street, Suite 100, Anchorage, Alaska 99501 USA.)
- SMITH, R. W., AND J. S. GRIFFITH. 1994. Survival of rainbow trout during their first winter in the Henrys Fork of the Snake River, Idaho. *Transactions of the American Fisheries Society* 123:747–756.
- STOTT, B. 1970. Some factors affecting the catching power of unbaited fish traps. *Journal of Fisheries Biology* 2:15–22.
- WALTERS, C. J., AND F. JUANES. 1993. Recruitment limitation as a consequence of natural selection for use of restricted feeding habitats and predation risk taking by juvenile fishes. *Canadian Journal of Fisheries and Aquatic Sciences* 50:2058–2070.
- 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.
- WEBSTER, J. R., AND H. M. VALETT. 2006. Solute dynamics. Pages 169–185 in F. R. Hauer and G. A. Lamberti (editors). *Methods in stream ecology*. Elsevier, San Diego, California.

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