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[Article]

Fish Passage Effectiveness of Recently Constructed Road Crossing Culverts in the Puget Sound Region of Washington State

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Abstract.—Fish passage barriers at road–stream crossings are widely recognized as salmon *Oncorhynchus* spp. habitat restoration priorities in Washington State and throughout the Pacific Northwest of the USA. More than 3,500 fish passage barriers (mostly culverts) have been repaired in Washington streams since 1999, costing more than US$139 million. We evaluated fish passage at 77 randomly selected culverts (new and repaired) that were issued permits during three time periods (1998, 2003, and 2007). This sample represents approximately 85% of the fish passage culverts permitted in the Puget Sound region of Washington State during the last 10 years. All study culverts were permitted for fish passage under the Washington Department of Fish and Wildlife's (WDFW) hydraulic project approval (HPA) permitting process and evaluated using physical criteria in the WDFW's fish passage barrier standard. Our results indicate that 30% of culverts (23 of 77) permitted under the HPA process for fish passage were, in fact, barriers. Culverts permitted as no-slope (one of the most common design types) or as an unknown design type were barriers in 45% of cases. Most culvert failures were due to noncompliance with permit provisions, particularly culvert slope, and a lack of critical evaluation of proposed plans in the context of site conditions by permitting biologists. We found no relationship between barrier status and permit date, experience of permitting biologists, quality of permit, or project sponsor type (private, public, or restoration entity). These results indicate the need for mechanisms to ensure better compliance from project sponsors and an improved process to critically evaluate the adequacy of proposed plans in the context of project site conditions.

Road crossings at rivers and streams are widely known to pose potential barriers to fish movement when fish passage structures such as culverts are improperly designed or installed (Bates et al. 2003). The consequences to fish populations associated with barriers at road crossings include the loss of habitat access for various life history stages, such as spawning or juvenile rearing (Beechie et al. 2006; Sheer and Steel 2006); genetic isolation (Reiman and Dunham 2000; Wofford et al. 2005; Neville et al. 2009); inaccessibility to refuge habitats from disturbance events such as floods, debris torrents, and fire (Dunham et al. 1997; Reeves et al. 1995; Lamberti et al. 1991); and extirpation (Winston et al. 1991; Kruse et al. 2001).

Because of their low cost relative to bridges, culverts are the most common fish passage structures at road crossings. Maintaining fish passage through culverts at road crossings is a substantial challenge because culverts are a fixed feature in a dynamic stream environment (Gubernick et al. 2003). As stream channels meander laterally and undulate vertically under shifting flow, sediment, and wood influences, unyielding culverts can become impediments to fish migration (Bates et al. 2003). Floods can magnify the influence of stream flow on culverts (Furniss et al. 1998).

Recent studies underscore the magnitude of the challenge presented by culverts both in terms of the sheer number of structures across the landscape and in their effectiveness in passing fish upstream. For example, the U.S. Forest Service and Bureau of Land Management reported that over 10,000 culverts exist on fish-bearing streams in federal lands of Washington and Oregon, and they estimated that at least half may be fish passage barriers (GAO 2001). The Washington State Department of Transportation alone owns 3,175 fish passage structures, of which 60% (1,893) were barriers (WDFW 2009). In Canada, Langill and Zamora (2002) found that 58.5% of the randomly selected new culverts in four counties of Nova Scotia were barriers while Gibson et al. (2005) found that 53% of culverts over a 210-km, newly constructed road network were barriers to fish in southern Labrador.

The importance of restoring fish passage at road crossings in Washington was heightened with the passage of the Salmon Recovery Act (1998) and the Forests and Fish Act (1999). All regional recovery plans for salmon *Oncorhynchus* spp. in Washington emphasize the importance of restoring fish passage at road crossings as a priority mechanism for rebuilding Endangered Species Act–listed salmon and steelhead *O. mykiss* populations. Likewise, Washington forest

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landowners are required to repair all fish passage barriers prior to 2016 in an agreement codified under Washington State law (Revised Code of Washington 76.09). Between 1999 and 2008, 3,500 fish passage barrier culverts were replaced with fish-passable structures, reportedly opening nearly 5,955 km of fish habitat in Washington streams (Governor's Salmon Recovery Office 2008). However, these estimates assume that the culverts were designed, permitted, and constructed to pass fish and that they will continue to pass fish through time.

Road Crossing Designs for Fish Passage

There are many accepted structures for fish passage, each with its own physical design criteria (Hotchkiss and Frei 2007). In Washington State, bridges, stream simulation culverts, hydraulic design culverts, and no-slope design culverts are the primary design types (Bates et al. 2003). Bridges are preferred because they allow most natural stream channel dynamics (lateral migration is a common exception) to occur. Stream simulation culverts are designed to mimic natural stream channels by creating a channel within the culvert that is similar to adjacent natural channels. By design, stream simulation culverts should present no more of an obstacle to fish and other aquatic organisms than the adjacent natural channel (Bates et al. 2003; Jackson 2003; Clarkin et al. 2005; Hotchkiss and Frei 2007). Hydraulic design culverts are engineered for the passage of specific target species and life stages (CDFG 2002). This type of culvert design is becoming increasingly rare in Washington because it relies on information about the physical swimming and leaping capabilities of specific fish species and life stages, which is generally unavailable for all but the strongest swimmers (Robison et al. 1999; CDFG 2002; Bates et al. 2003; Coffman 2005). No-slope culverts are designed to be installed in low-gradient streams ($<3\%$) and are desirable if stream conditions are appropriate because the engineering requirements are simpler and the costs lower for this type than other design options (Bates et al. 2003). Bottomless culverts, which are relatively common across the landscape, are not considered a specific design type but can be constructed under a stream simulation or no-slope design. Regardless of design type, all culverts permitted for fish passage in Washington are supposed to accommodate 100-year flood events.

Fish Passage Regulation in Washington Streams

The Washington Department of Fish and Wildlife (WDFW) administers the "hydraulic code" (Revised Code of Washington 77.55), which regulates work that uses, obstructs, diverts, or changes the natural flow or bed of state waters for the protection of fish life. The WDFW implements the law via the hydraulic project approval (HPA) permit process. Permits issued by the WDFW include a list of provisions unique to the permit type and physical setting that attempts to avoid, minimize, or mitigate for activities that may affect fish life in Washington's lakes, streams, rivers, and marine environments. Annually, the WDFW issues approximately 4,500 HPA permits, of which some 400 relate to fish passage structures in streams (WDFW 2006). The department's HPA jurisdiction does not extend to tribal lands, and HPA permits are not typically issued on U.S. Forest Service lands.

In 2007, the results of a WFDW pilot study suggested that there were inconsistencies in compliance, implementation, and effectiveness of five HPA permit types, including fish passage structures (Quinn et al. 2007). Prior to the completion of that qualitative study, the capacity of the HPA program to protect aquatic resources had not been examined.

In Washington State, unimpeded fish passage is mandatory where roads cross fish streams (Revised Code of Washington 77.57), and HPA permit provisions are intended to ensure that new or replacement road crossings meet fish passage standards. Almost all fish passage HPA permit requests receive a field review from a WDFW biologist to help ensure that designs for road crossings meet the requirements for fish passage. In spite of their importance to fish and cost to landowners, the effectiveness of fish passage culverts have not been quantitatively evaluated to determine whether they are appropriately permitted, designed, or installed to maintain fish passage through time. Although substantial research has been conducted on the design of culverts (Bates et al. 2003; Coffman 2005; Hotchkiss and Frei 2007), assessments of fish passage after culverts are installed is less common, probably because of the cost associated with compliance and effectiveness monitoring, as has been the case in Washington State. We evaluated culverts permitted for fish passage in 2007, 2003, and 1998 to determine their ability to pass fish and to retain the physical characteristics for which they were designed. We were also interested in understanding how the permitting process may have contributed to the installation of culverts resulting in fish passage barriers.

Study Area

The Puget Sound landscape of Washington State has been extensively shaped by the Wisconsin glaciations and tectonic activity over the past 10,000 years (Booth et al. 2003). Immature soils over expansive layers of glacial outwash and glacial till support large tracts of commercial and federal temperate forests in headwater stream reaches with rapidly urbanized development occurring adjacent to large lowland rivers (Franklin and Dyrness 1973; Booth 1991). Puget Sound is a large fjord that is bracketed by the steeply rising Olympic Mountains (~1,500 m) to the west and the Cascade Range (~2,200 m) to the east (with Mt. Rainier at 4,300 m). Annual precipitation, largely rain, ranges from 50 to 250 cm between November and March. About 4.2 million people currently live in the Puget Sound area.

There are more than 10,000 streams in the Puget Sound basin. Lombard (2006) suggests that the basin is unique by virtue of both its high salmon species richness and high natural salmon productivity (historically among the greatest in the world). However, Gresh et al. (2000) estimate that salmon abundance has decreased 92% in Puget Sound streams since 1850.

Methods

Field sampling.—We estimate that approximately 3,223 fish passage structures of all types were permitted in the Puget Sound region in the last 10 years. We used a randomly stratified sampling design whereby we randomly selected 30–50 HPA permits in each of 1998, 2003, and 2007 from the Puget Sound region. We selected permits from these three time periods so that we could compare permit compliance and effectiveness among—and trends across—time periods. We limited our study to culverts permitted since 1998 because prior to that date GPS coordinates, which are critical for locating those culverts, were mostly absent. Although installation dates were not available for most permitted culverts, surveys of permitting biologists suggested that about 85% of culverts are installed within 12 months and 95% within 24 months of the time they are permitted.

Only permits featuring the installation of a new or replacement permanent culvert were retained in the sampling pool. We omitted permits that involved modifying an existing culvert with baffles, fishways (ladders), or realignments. We also omitted culverts that were obviously permitted using a stream simulation design because they were evaluated in a separate, ongoing study (Bob Barnard, WDFW). We did not include bridges or emergency or temporary culverts in this study. Where single permits authorized the installation of multiple fish-passable culverts, we randomly selected one culvert for inclusion to minimize any bias associated with evaluating multiple culverts constructed by a single contractor or subjected to a single localized disturbance. As defined here, an HPA permit includes the authorizing permit, associated application, construction plans, and other correspondence. After screening for the criteria above, 110 HPA permits were retained in the sample pool, which represents approximately 2,740 (85%) of the original 3,223 fish passage structures permitted in the last 10 years.

Field evaluations were performed by a geomorphologist and two biological technicians between November 2008 and June 2009. Before visiting a project site, the evaluation team gathered the HPA permit and contacted the landowner for permission to access the site and ensure that the culvert had been installed.

Barrier assessments.—Culverts were evaluated for fish passage effectiveness using WDFW's fish passage assessment methodology and barrier standard (WDFW 2000), which has been the legal passage standard under state law since 1994 (Washington Administrative Code 220-110). All fish passage culverts approved through the HPA permit process since 1994 are designed to pass this legal standard. This assessment can render a passable versus nonpassable determination on any fish passage culvert, regardless of design type and who installed the structure. The barrier standard is based on the swimming and leaping capabilities of a 15.24-cm (6-in) trout. A culvert designated as a barrier may not block all of the fish attempting to pass. Each culvert was evaluated using level A (and, where necessary, level B) analysis (Figure 1), which incorporates stream and culvert parameters associated with fish passage limitations (Table 1). Level B uses a hydraulic model to determine average water velocity in the culvert. If the velocity exceeds the swimming capability of a specific fish species for more than 10% of the time during the months of migration, the culvert is considered a barrier.

We were also interested in how measurement error might affect the barrier assessment results. To help validate evaluation team results, an independent review team reevaluated a random subset of 18 culverts using the same field methodology. The review team, composed of culvert review specialists in the WDFW, conducted their assessment with no knowledge of the evaluation team's results. To evaluate the potential effect of systematic measurement error (bias), we regressed evaluation team data on review team data for each of four parameters: culvert span, slope, length, and bankfull width. We assumed that the review team data were collected without error and that any difference between review and evaluation team data was attributable to evaluation team measurement error. Because culvert slope measurement error was large relative to the other characteristics and because slope appeared to be one of the more important criteria for passage (see below), we conducted a simple sensitivity analysis of our findings relative to slope measurement error. We used the slope regression equation between teams to calculate the 95% confidence interval (CI) for

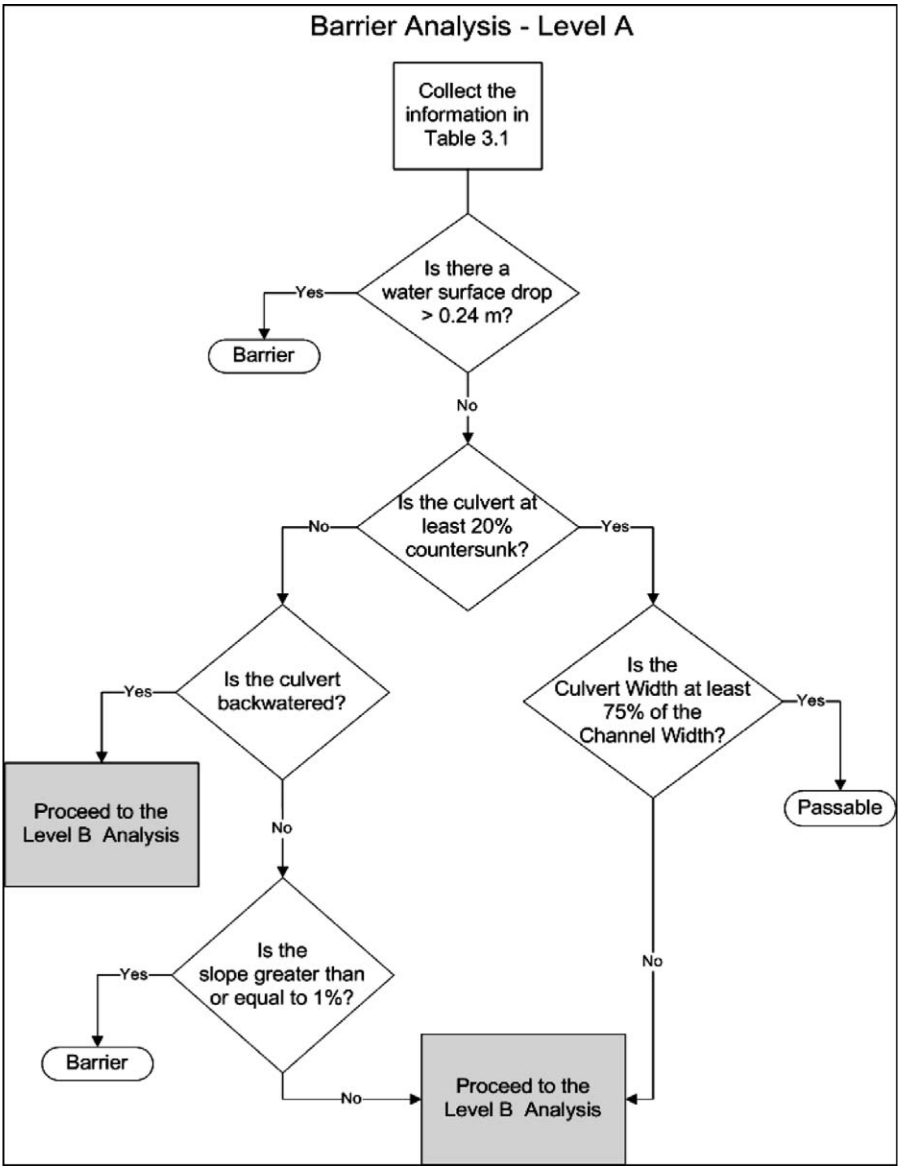

FIGURE 1.—Level A analysis (WDFW 2000) for determining the fish barrier status of culverts in Washington State.

TABLE 1.—Culvert characteristics associated with possible fish passage barrier types (modified from Coffman 2005).

Culvert characteristic	Possible barrier
Culvert outlet drop	Jump barrier
Culvert slope	Velocity barrier
Culvert slope and length	Exhaustion barrier
Natural stream substrate	Depth or velocity barrier
Culvert span : stream width ratio	Velocity and depth barrier

each of the 77 slopes collected by the evaluation team (Zar 2009). We then subtracted half the width of the 95% CI from each slope value measured in the field by the evaluation team and reassessed all culverts. In effect, subtracting the measurement error in this way assumes that the evaluation team consistently overestimated culvert slope and thus the percentage of culverts determined to be barriers.

Culvert design assessment.—Culverts permitted in Washington State are supposed to follow one of three

TABLE 2.—Design criteria for no-slope and stream simulation culvert design types.

Criterion	No-slope design	Stream simulation design
Culvert slope	0 ± 0.5%	Equal to stream slope
Span	Streambed width inside the culvert = bankfull width	(1.2 × channel width) + 0.61 m
Countersunk	≥20% at outlet and ≤40% at inlet	30–50%

design types: no-slope, hydraulic, or stream simulation. Each design type includes specific criteria or physical standards (Table 2) that, if met, are assumed to pass fish (Bates et al. 2003; Hotchkiss and Frei 2007). Design type and design criteria, which are often in the form of permit provisions, are supposed to be made explicit in HPA permit paperwork.

We were interested in understanding how fish passage structures of different design types—alone and in combination with design criteria—performed through time. Design type and criteria information is important for two reasons: (1) the failure of an appropriate (to the site) design type installed with the correct design criteria indicates that the design type may not have been as robust to stream dynamics as previously believed and (2) even with a suitable design type, culverts installed with substandard design criteria are more likely to form fish passage barriers in the future.

Bottomless culverts were not judged according to a specific design type because there was no way to classify them to one of the three types based on permit provisions. Instead, we classified bottomless culverts as if they were an independent culvert design type.

Where the design type was not explicit in the permit paperwork, we assigned a design type based on the provisions (design criteria) contained in the permit using the following process. If the permit described the culvert as bottomless, it was assigned to the "bottomless" culvert type (as described above). If the permit contained all three no-slope provisions or all three stream simulation provisions, the culvert was classified as a no-slope or stream simulation type, respectively. Culverts with permit provisions that did not meet

TABLE 3.—Variables used in the classification and regression tree analysis.

Category	Independent variables	Data type	Count (categorical) or range (continuous)
Human	Biologist experience	Continuous	71–5,567 d (mean = 1,670)
	Project sponsor		
	Public	Categorical	27
	Private	Categorical	39
	Restoration	Categorical	11
Environmental	Latitude	Continuous	46.700–49.000°N
	Longitude	Continuous	−123.700 to −121.800°W
	Land Use		
	Urban	Categorical	17
	Rural	Categorical	32
	Agriculture	Categorical	2
	Forestry	Categorical	10
	Highway	Categorical	16
	Channel width	Continuous	0.8–11.3 m (mean = 3.3)
Provisional	Provision score	Continuous	0–100
	Slope violation	Bivariate	Yes/No
	Span violation	Bivariate	Yes/No
	Length violation	Bivariate	Yes/No
Culvert type	Culvert shape		
	Round	Categorical	32
	Squash	Categorical	11
	Elliptical	Categorical	3
	Box	Categorical	5
	Arch	Categorical	24
	Material		
	Aluminum	Categorical	2
	Concrete	Categorical	27
	Plastic	Categorical	3
	Corrugated metal	Categorical	43
Time	Permit year		
	1998	Categorical	25
	2003	Categorical	32
	2007	Categorical	20

TABLE 4.—Sample pool of hydraulic project approval (HPA) permits by year and reasons for excluding permits from fish passage effectiveness study.

Permit review	1998	2003	2007	Total
Initial HPA sample pool	32	45	33	110
Landowner denied access	0	2	0	2
Existing culvert not replaced	2	3	11	16
Nonfish stream	0	5	1	6
Data collection incomplete	2	1	0	3
Site not found	3	2	1	6
Permits reviewed for analyses	25	32	20	77

bottomless, no-slope, or stream simulation designs were assigned to an "unknown design" type.

After culverts were assigned a design type, we evaluated the physical characteristics of the fish passage structures in the field against the design criteria for that type (Table 2). The characteristics of culverts of unknown design type and those identified as no-slope were compared with the no-slope criteria to better understand what attributes may have contributed to deviations from known design standards.

Assessing permit provisions.—We conducted analyses of permit provisions to better understand how guidance in the permit might be related to barrier status. We assessed each permit for the presence of five HPA provisions that are important in all fish passage permits: minimum culvert span (width), maximum culvert length, maximum culvert slope, countersinking the culvert outlet to at least 20% of culvert height, and sizing the streambed width inside the culvert relative to the streambed width of the stream channel. A provision was considered present only if it was explicitly written in the HPA permit, associated permit application, or referenced construction plans. Presence of a provision received a value of 1, and absence of a provision received a value of 0. Provision score was defined as the sum of provisions present in a permit divided by total number of provisions possible (up to five) in that HPA permit. Provision rate was defined as the number of permits that had a particular provision divided by total number of permits for which that provision was applicable. There is a provision score for each permit and a provision rate for each of the five provisions. We did not conduct assessments on specific provisions when those provisions were likely to have been included in missing paperwork.

Compliance analysis.—We evaluated whether compliance with HPA provisions was associated with culvert barrier status. Compliance assessments compared HPA permit provisions with physical conditions measured in the field. Compliance assessments were only conducted for culvert span, length, and slope differences, that is, characteristics that could not change due to postconstruction stream dynamics. A culvert slope with more than a 1% difference between the measured slope and the permitted slope was defined as noncompliant. Likewise, a measured culvert span that was less than 10% of the permitted span and a measured culvert length that was more than 10% of the permitted length were defined as noncompliant.

Explaining barrier status.—We analyzed 13 parameters using a classification and regression tree (CART) to help determine which culvert attributes not considered in the level A or B assessment might best explain culvert failure rate (Table 3). The classification tree process iteratively determines the most explanatory path in describing barrier status from predictor variables. The classification stops when there is no additional predictive value among variables (Systat 2007).

Statistical analysis.—We examined continuous variables for normality using a Shapiro–Wilk test before conducting statistical comparisons. When variables were not normally distributed ($P < 0.05$), we used nonparametric tests. All determinations of statistical significance were made at the 0.05 level. We compared differences in the proportion of passable to impassible culverts by time period using a chi-square goodness-of-fit test. A Mann–Whitney rank-sum test was used to test the hypothesis that fish passage barriers were more common among the least experienced permitting biologists. A Fisher's exact test was used to determine whether fish passage was different among project sponsors. Mean provision scores were compared among permit years using a Kruskal–Wallis test.

Results

Of the 110 HPA permits retained in the original sample pool, we excluded 33 for a variety of reasons, including that the culvert (re)placement was not completed ($n = 16$), the culvert was located on a non-fish-bearing stream ($n = 6$), we were unable to locate the site ($n = 6$), data collection was incomplete ($n = 3$), and the landowner denied us access to the site ($n = 2$; Table 4). There were six permits that contained multiple culverts (mean = 2.6 culverts/multiculvert permit; SD = 0.82) from which we randomly selected one culvert from each permit for inclusion in this study. We evaluated the remaining 77 culverts, including 25 from 1998, 32 from 2003, and 20 from 2007.

Barrier Analysis

Of the 77 culverts evaluated through level A and B assessments, 23 (30%) were fish passage barriers (Figure 2). Two culverts "washed out" between installation and our study and were considered barriers because they represented failed culverts. Two culverts

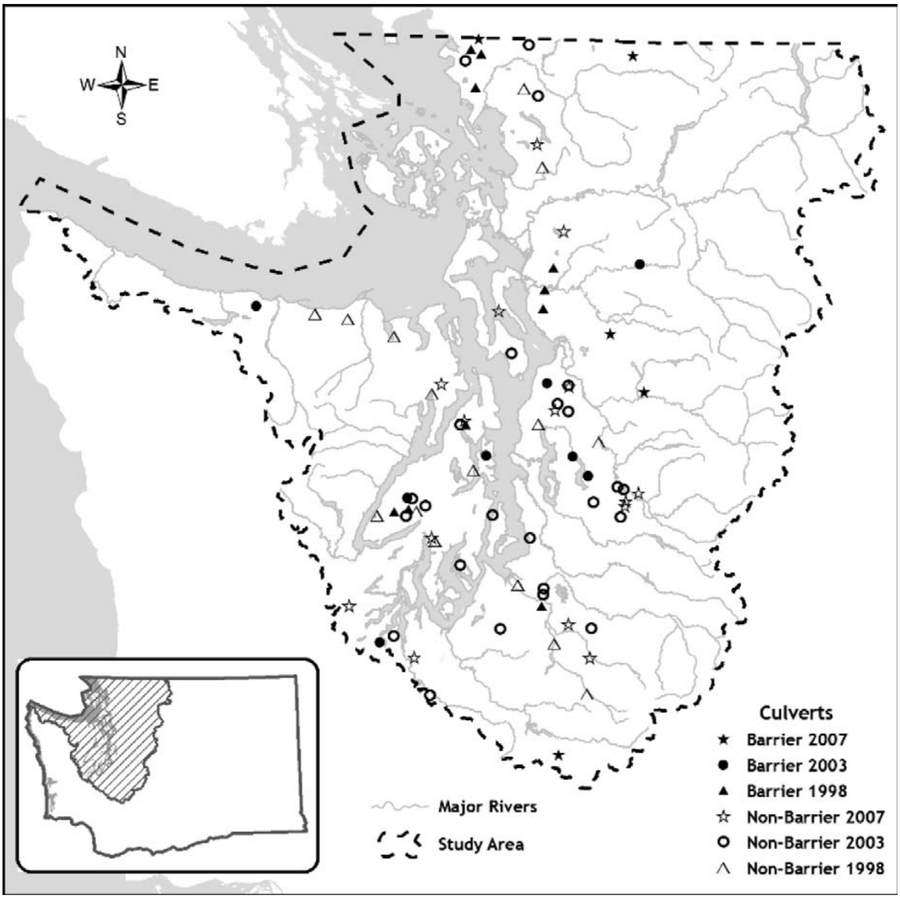

FIGURE 2.—Culvert study site locations within the Puget Sound basin showing barrier and nonbarrier culverts and the years in which they were permitted.

were classified as barriers solely because their outfall drop exceeded fish jumping capability standards (>0.24 m), and all eight structures with an outfall drop of 0.10 m or more were ultimately classified as barriers due to lack of stream substrate in the culvert and excessive culvert slope.

Culverts were classified as barriers primarily for two interrelated reasons: they were not countersunk at least 20% into the streambed, and they were placed at a greater than 1% slope (Figure 3). The presence of stream substrate to at least 20% of the culvert rise was a good indicator of passability. All 50 culverts countersunk at least 20% (or that were bottomless) were fish passable, while 23 of 27 (85%) of the culverts countersunk less than 20% were barriers.

There was no statistical difference between the proportions of passable to impassible culverts by year for the full data set ($\chi^2 = 1.81$, df = 2, $n = 77$, $P = 0.404$), although the oldest culverts tended to have slightly higher barrier proportions than newer culverts (Table 5).

The evaluation and review teams independently identified the same 7 culverts as barriers out of the 18 culverts reviewed. Data collected by the evaluation team and the review team were most similar for culvert length and span, whereas bankfull widths and culvert slopes were more divergent (Table 6). Barrier status did not change for any culvert after adjusting for 95% CI slope measurement error (Figure 4).

Noncompliance with slope provisions was the only significant variable identified in the CART analysis ($P = 0.003$) that was related to barrier status. The CART analysis suggested that culverts installed with slopes that exceeded the permitted slopes by 1% or more had a 69% chance of becoming fish passage barriers even when percent slope alone did not qualify them as impassable in the level A and B barrier analysis. Of the

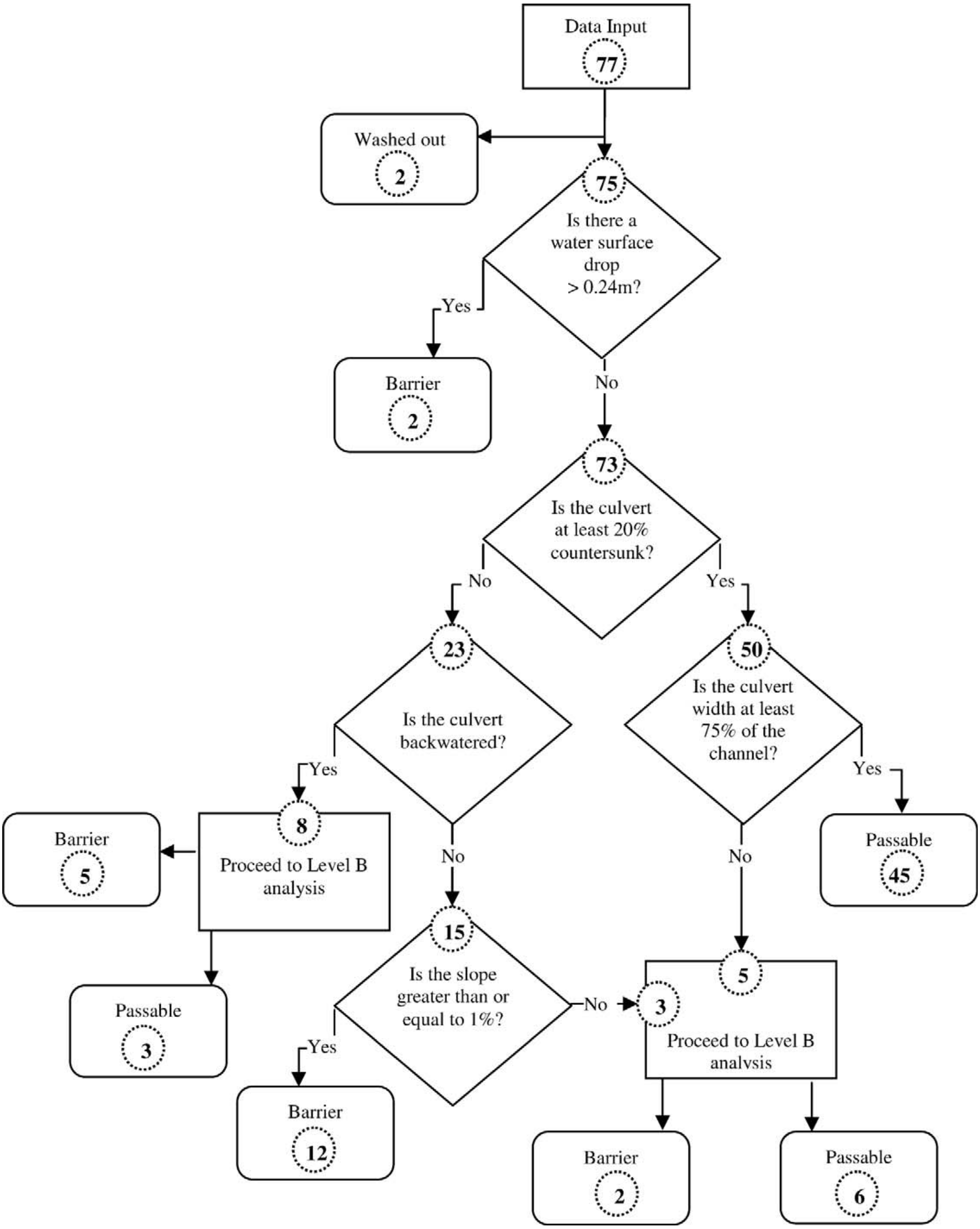

FIGURE 3.—Flow chart showing the results for 77 culverts assessed for passability in the Puget Sound basin in 2008–2009.

14 no-slope culverts that were barriers, 9 (64%) were noncompliant with slope provisions.

The CART results were consistent with some individual comparison results. Permitting biologist experience was not associated with barrier status (Mann–Whitney $U = 564.0$, $P = 0.529$). Median biologist experience and its interquartile range were similar between projects classified as barriers (median

TABLE 5.—Number and percent of fish passage barriers by year.

	Bottomless included		Bottomless excluded	
Permit year (n)	Barriers (%)	Nonbarriers	Barriers (%)	Nonbarriers
2007 (20)	5 (25)	15	5 (38)	8
2003 (32)	8 (25)	24	8 (40)	12
1998 (25)	10 (40)	15	10 (50)	10
Total (77)	23 (30)	54	23 (43)	30

= 855 d, range = 1,934 d, n = 23) and those not classified as barriers (median = 921 d, range = 2,714 d, n = 54; Figure 5). Likewise, there was no statistical difference in barrier status between culverts installed by restoration sponsors and nonrestoration sponsors (Fisher's exact test; $P = 0.490$). Excluding the two culverts that washed out did not change this result ($P = 0.266$), although the small sample size for restoration sponsors may limit the ability to distinguish among project sponsors (Figure 6).

Culvert Design Assessment

We determined that 31 culverts were permitted with provisions for the no-slope design, 2 were permitted for the stream simulation design, 24 were permitted as bottomless structures, and 20 were permitted with no apparent design (unknown design). There was no evidence (i.e., reference to fish species, swimming or jumping ability, or water velocity measurements) to suggest that the hydraulic design was used in any of the HPA permits. Of the 31 culverts permitted with provisions for the no-slope design, 26 (84%) did not meet the no-slope design criteria as measured in the field and 14 (45%) resulted in fish passage barriers (Table 7). All bottomless structures (n = 24) were classified as fish passable. Two culverts permitted under the stream simulation design (and inadvertently included in the study) were passable. Although U.S. Forest Service culverts are not normally permitted under the HPA permit system, one such culvert was nevertheless included in the study and it was not passable.

Of the 20 culverts in the unknown design category, 2 met the stream simulation design criteria as determined by field measurement and were passable. The other 18 culverts in the unknown design category were inconsistent with the no-slope and stream simulation design criteria, and 9 (50%) were fish passage barriers.

Culverts identified as no-slope but failing to meet the design criteria for that type (n = 26; Table 7) plus unknown culvert designs (n = 18; Table 7) tended to be narrow relative to channel width. As measured in the field, the mean span-to-bankfull width ratio for stream simulation design culverts was 1.56:1, that for bottomless design culverts was 1.17:1, and that for no-slope and unknown design culverts was 0.72:1. Inadequate countersinking (i.e., <20%) and excessive slope (>1% slope difference) were also common in unknown designs. Culverts never failed to meet design criteria solely because they were inadequately countersunk, and only two failed solely because of excessive slope (Figure 7).

Compliance Assessment

Culvert installation was in compliance with the culvert slope provision in 32 of 49 (65%) cases (Figure 8). Culverts with noncompliant slopes (i.e., >1% slope difference) were more likely to be barriers (11 of 17) than culverts in compliance (5 of 32; Fisher's exact test; $P = 0.001$). Slope was not measured at 17 of 24 bottomless culverts, and some HPA permits (n = 12) lacked a slope provision for comparison.

Compliance with culvert span provisions was 85% (Figure 9) and not associated with barrier status (Fisher's exact test; $P = 0.689$). Of the nine culverts that were installed at least 10% smaller than permitted (noncompliance), three were barriers and six were passable. Of the culverts that were at least 10% larger than were permitted, three were barriers and 12 were passable. Data for 18 sites were not included in the span compliance analysis because span provisions were not included in the HPA permits (n = 4), referenced plans were not available for review (n = 8), or the HPA permit referenced "streambed width" without explicitly including a value for span (n = 6).

Compliance with culvert length provisions was 85% (Figure 10) and not associated with barrier status (Fisher's exact test; $P = 0.343$). Of seven culverts that

TABLE 6.—Comparisons between the mean (SD) measurements by the evaluation (ET) and review (RT) assessment teams and regression equations for bankfull width and culvert slope, length, and span.

Variable (n)	Evaluation team	Review team	Regression equation (r^2)
Bankfull width (21)	3.7 m (2.7)	4.3 m (3.3)	$\mathrm{ET} = 0.575 + 0.729 \cdot \mathrm{RT}$ (0.83)
Culvert slope (18)	1.8 % (2.0)	1.7 % (1.8)	$\mathrm{ET} = 0.329 + 0.898 \cdot \mathrm{RT}$ (0.66)
Culvert length (22)	18.0 m (9.3)	18.6 m (9.3)	$\mathrm{ET} = -0.271 + 0.981 \cdot \mathrm{RT}$ (0.97)
Culvert span (22)	2.9 m (2.5)	2.8 m (2.3)	$\mathrm{ET} = -0.124 + 1.049 \cdot \mathrm{RT}$ (0.99)

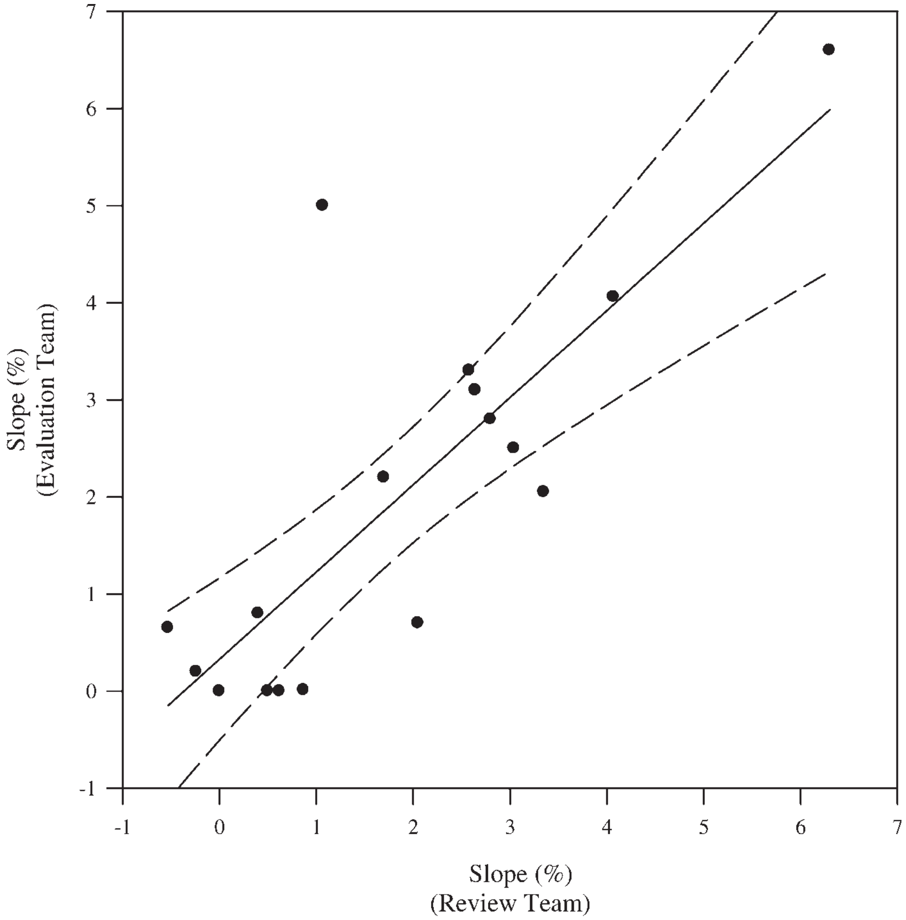

FIGURE 4.—Regression line between the slope measurements of the evaluation and review teams for 18 culverts. The dashed lines depict the 95% confidence limits. The lower confidence limits were applied to the slopes measured by the evaluation team to correct for potential measurement error.

were at least 10% longer than permitted (noncompliance), three were barriers. One of five culverts that was 10% shorter than permitted was a barrier. Culvert length provisions were not included in 10 HPA permits, and some paperwork was not available for 14 HPA permits.

Provision Assessment

The proportion of important provisions contained in an HPA permit (i.e., provision score) among HPA permits ranged from 0 to 100 (median = 90). There was no significant difference in provision scores between barrier and fish-passable culverts (Mann–Whitney $U =$ 573.0, $P = 0.560$), although barrier culverts tended to have slightly lower provision scores (Figure 11). Provision scores were significantly different among permit years (Kruskal–Wallis test; $H = 6.967$, df = 2, $P < 0.031$). Median provision scores were 80, 100, and 80 for permits written in 1998, 2003, and 2007, respectively (Figure 12).

The proportion of HPA permits that included all three of the most important provision types (countersunk depth, culvert slope, and culvert span) was 71% (52 of 73), and there was no significant difference in the proportion of barriers with and without these three provisions (Fisher's exact test; $P = 0.777$). The proportion of HPA permits containing an important provision (i.e., provision rate) varied among the five permit provisions and through time (Table 8). The provision requiring "substrate width inside the culvert to equal substrate width outside the culvert" was present in 74% of HPA permits overall but decreased through time from 84% in 1998 to 55% in 2007. Culvert length was the only provision included in all permits during a single time period (2003).

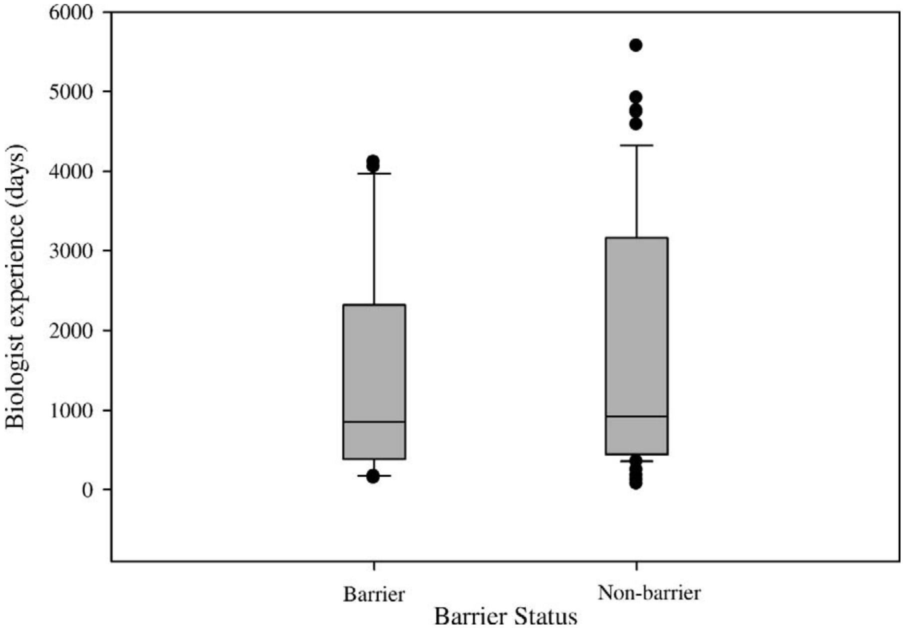

FIGURE 5.—Relationship between biologist experience (d) in writing HPA permits and barrier/nonbarrier status of culverts.

Discussion

In this study, 30% of HPA permitted culverts on fish-bearing streams in the Puget Sound area of Washington State were determined to be barriers to fish. These results were consistent across three time periods and across different land-use types. Moreover, these results were robust to sampling error. The evaluation and review teams independently identified the same 7 culverts as barriers out of the 18 culverts reviewed. Even the simple sensitivity analysis, which reduced the evaluation team's culvert slope measurements by half of the 95% confidence interval, had no effect on the proportion of passable to impassible culverts. Although certain culverts were excluded from the study (i.e., stream simulation designs, emergency and temporary culverts, and retro fixes), we estimate that our study sample represents approximately 85% of fish passage culverts permitted in the Puget Sound region of Washington State during the last 10 years.

Barrier status varied by culvert design type. Of the 31 culverts identified as no-slope from HPA permit paperwork, 14 (45%) were fish passage barriers. Similarly, of the 18 culverts identified as unknown

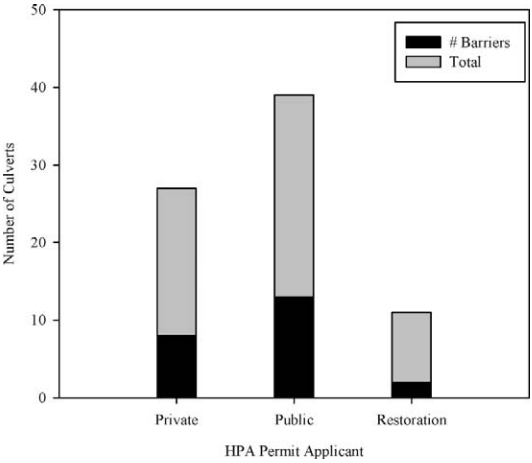

FIGURE 6.—Number of culverts by barrier/nonbarrier status and type of permit applicant.

TABLE 7.—Permitted culvert design types and their current status in meeting design criteria and the level A and B barrier standards (see text). Twenty permits did not include specific provisions to allow classification as either no-slope or stream simulation and are referred to as of "unknown design".

Design	Number permitted	Number (%) currently failing to meet design criteria	Number (%) barriers
No-slope	31	26 (84)	14 (45)
Stream simulation	2	0	0
Bottomless	24	0	0
Unknown	20	18 (90)[a]	9 (50)

[a] Two culverts permitted with unknown designs ultimately met physical criteria for stream simulation.

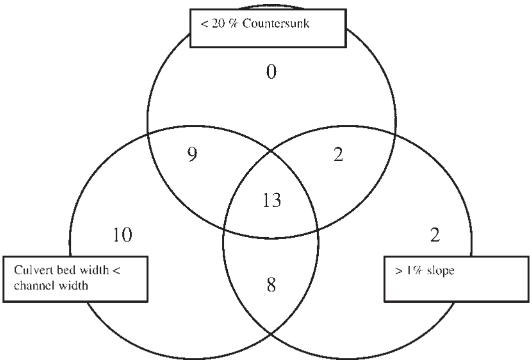

FIGURE 7.—Venn diagram showing the no-slope design criteria thresholds and the ways in which 44 culverts failed to meet the criteria of the no-slope or stream simulation designs in terms of those thresholds.

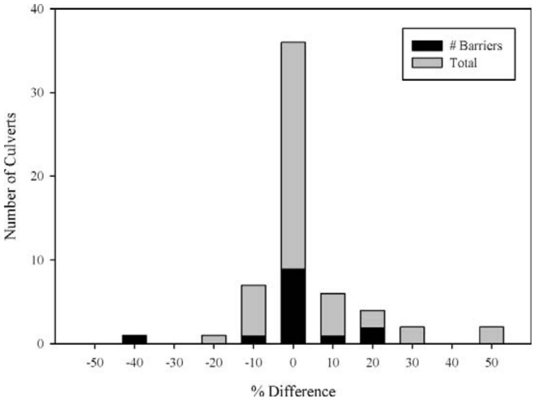

FIGURE 9.—Number of culverts by barrier/nonbarrier status and percent difference between permitted and installed spans. Positive values represent culverts with greater spans than were permitted, negative values culverts with lesser spans. Of the 9 structures that were at least 10% smaller than permitted (noncompliant), 2 were barriers.

designs, 9 (50%) were fish passage barriers. Bottomless culverts were considered independently of other design types because it was frequently impossible to determine the intended design (no-slope versus stream simulation) from HPA permits alone, and results suggested that fish passage effectiveness differs between bottomless culverts and other designs. All 24 bottomless structures assessed in this study were passable. Although we attempted to exclude stream simulation culverts from this study, the four that were inadvertently included were fish passable structures.

Appropriate culvert design must consider human safety, cost, and fish passage (Bates et al. 2003). The fact that all bottomless culverts were passable may be a by-product of engineering safety margins designed into these structures since these types of culverts are more susceptible to road failure than other design types (Kerenyi and Pagan-Ortiz 2007). In this study, bottomless culverts were installed with spans that commonly exceeded bankfull steam width whereas no-slope culverts tended to be undersized. Although no bottomless culverts were classified as barriers in this study, we observed scour of the culvert footings in several structures, which could ultimately undermine the integrity of the road prism associated with these culverts.

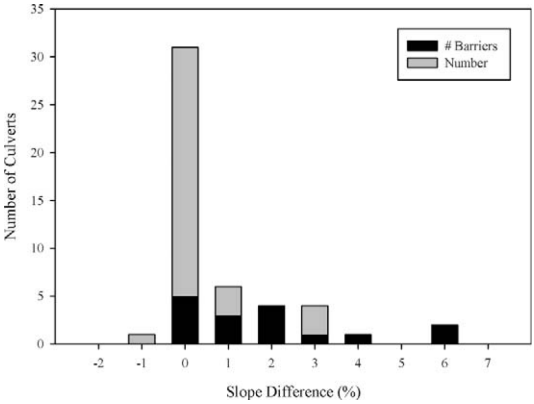

FIGURE 8.—Number of culverts by barrier/nonbarrier status and the difference between installed and permitted slopes. Positive values represent culverts with greater slopes than were permitted, negative values culverts with lesser slopes. Of 49 culverts, 17 were out of compliance, 11 of which resulted in barriers to fish passage.

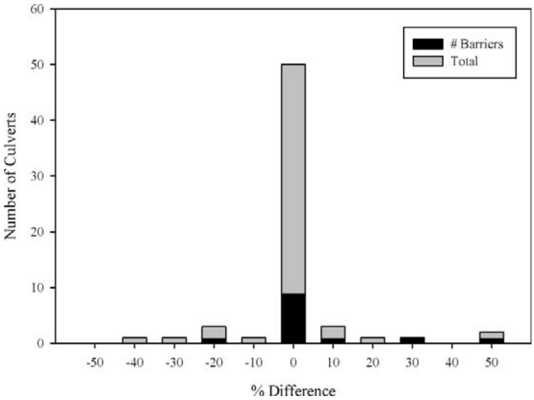

FIGURE 10.—Number of culverts by barrier/nonbarrier status and percent difference between permitted and installed lengths. Positive values represent culverts with greater lengths than were permitted, negative values culverts with lesser lengths. Of the 7 structures that were at least 10% longer than permitted (noncompliant), 3 were barriers.

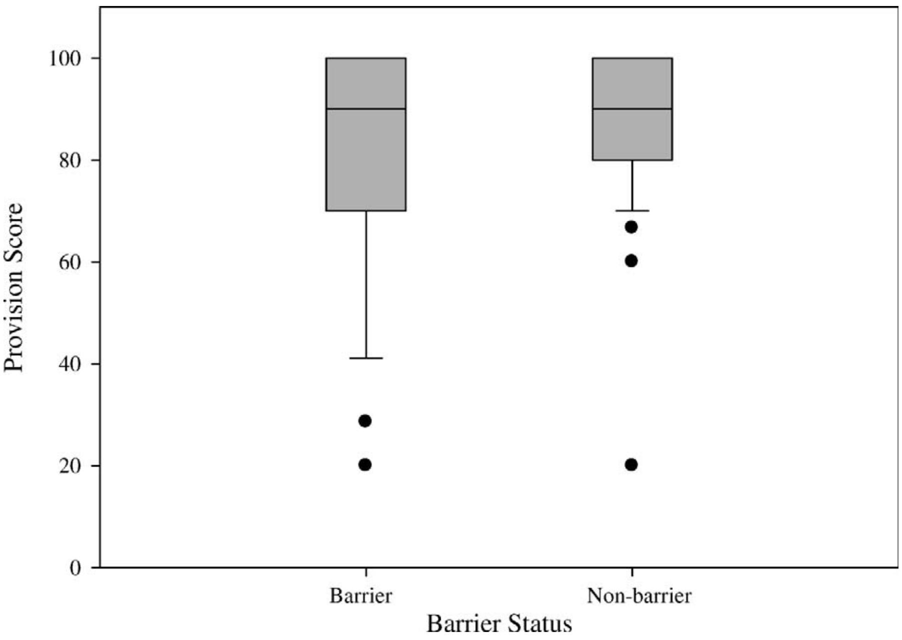

FIGURE 11.—Provision scores (proportion of important provisions contained in an HPA permit) by barrier/nonbarrier status.

Providing fish passage at road–stream crossings is an important salmon recovery tool in the Pacific Northwest of the United States and Canada. Washington's *State of the Salmon in Watersheds Report* accounts for fish passage barriers corrected and provides an estimate of stream miles opened as a result of those efforts. Between 1999 and 2008, more than 3,500 fish passage barriers have been replaced with fish-passable structures (Governor's Salmon Recovery Office 2008). Prior to the current study, quantitative efforts to assess the effectiveness of fish passage installations have not been conducted in Washington State. Since 1999, at least US$139 million has been spent on salmon recovery efforts in Washington in which fish passage barrier correction was the targeted restoration activity (D. Caudill, Washington Recreation and Conservation Office, personal communication). Fish passage projects that fail to correct fish passage barriers are not only a waste of money, in cases where there is no monitoring they may result in blockages that remain for the life of the structure, which in some cases is up to 50 years.

Comparable studies evaluating fish passage at road–stream crossings where culverts were individually permitted for fish passage are uncommon. Quinn et al. (2007) observed that the implementation rate of culvert size and installation requirements was approximately 50% for 14 recently constructed culverts in western Washington. Gibson et al. (2005) found that 53% of the culverts examined on a newly constructed road in Labrador were barriers and failed to follow required Department of Fisheries and Oceans guidelines. Broad-scale compliance and effectiveness studies of aquatic habitat restoration are rare despite the need for cost-effective feedback on expensive and time-consuming actions (Roni et al. 2005; Reeve et al. 2006).

Determining why a high proportion of relatively new structures failed the fish passage barrier threshold is complex. The 35% rate of noncompliance with culvert slope provisions in HPA permits was a statistically

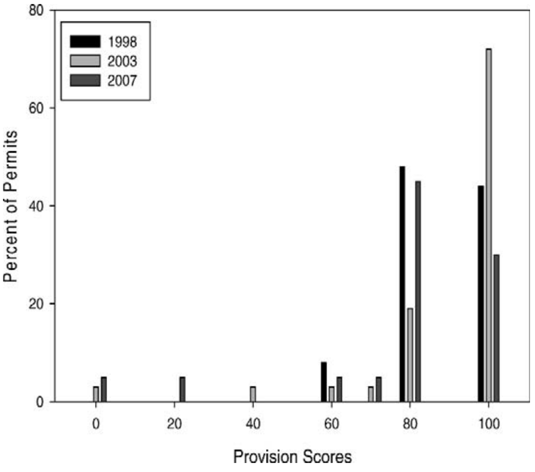

FIGURE 12.—Provision scores for 77 HPA permits by year.

TABLE 8.—Provision rate (%) for five provisions considered important for inclusion in all HPA permits issued for fish passage; the numbers of permits applicable to each provision are given in parentheses.

Provision	1-Year	5-Year	10-Year	Mean
Minimum culvert span	90 (20)	96 (28)	95 (21)	94 (69)
Culvert sediment width relative to streambed width	55 (20)	78 (32)	84 (25)	74 (77)
Maximum culvert slope	74 (19)	97 (29)	92 (25)	89 (73)
Maximum culvert length	84 (19)	100 (29)	67 (21)	86 (69)
Countersink culvert at outlet	80 (20)	84 (32)	96 (25)	87 (77)

significant attribute in predicting fish passage barrier status. Also, 12 culverts were judged impassable because they did not retain adequate sediment in addition to excessive slope. It is unlikely that cost-cutting measures by project sponsors are responsible for slope noncompliance, as has been observed in Canada (Gibson et al. 2005). Reducing culvert size relative to permit provisions is a more effective means of reducing cost, but compliance for culvert span and length were each 85% and neither was significantly associated with fish passage barrier status. We believe that improper installation in regards to slope is a major factor in the construction of fish passage barriers, especially for the no-slope culvert design. In contrast, low span : bankfull width ratios appeared to contribute to high failure rates despite the fact that those culverts were often compliant with the permit provision for span. In other words, culvert span was inadequately designed by applicants and subsequently approved by the WDFW.

The HPA permits issued by the WDFW contain provisions tailored to specific site conditions. However, we found no association between provision scores and barrier status. In other words, the quality of the HPA permit as measured by provision scores was not a predictor of barrier status. Likewise, permitting biologist experience (days employed in the HPA permit program) was not a useful predictor of barrier status, although experienced biologists tended to have slightly fewer fish passage barriers associated with their HPA permits than inexperienced biologists.

Culvert span, countersunk depth, and slope criteria are the most important dimensions of culvert specification (Bates et al. 2003). The proportion of HPA permits that included all three of these necessary provision types was low (71%), although the inclusion of all three provisions was not related to barrier status. Culvert span was provisioned in 94% of permits, comparable to the observations of Quinn et al. (2007), who found a provision rate of 91% in a similar study. Culvert slope was included in 74% and 97% of HPA permits in 2007 and 2003, respectively. Quinn et al. (2007) observed a provision rate of 64% for culvert slope. We did not observe a consistent trend in provision rates among permit years. Rates improved from 1998 to 2003 for four of five provision types; however, they decreased for all five types from 2003 to 2007.

An inherent assumption in reporting fish passage barrier progress via permits for barrier correction, as is done in Washington's *State of the Salmon in Watersheds Report* (GSRO 2008), is that the proposed structure was actually installed. Of the permits that were randomly drawn for this study, 6.3% (2 of 32) 10-year permits and 6.7% (3 of 45) 5-year permits were never implemented. Langill and Zamora (2002) noted that in Nova Scotia 12% of proposed structures were not installed after notification to officials. These results indicate that progress in repairing fish passage barriers is slower than suggested by the rate of permit issuance.

Providing fish passage at road crossings is perhaps the least controversial restoration action since it can result in an immediate gain in the amount of fish habitat and the uncertainty associated with the action is relatively low (Roni et al. 2002). Bates et al. (2003) suggested that no-slope culvert designs, in particular, are relatively simple to install and require minimal engineering and surveying efforts. However, we found a high proportion of impassable no-slope design culverts permitted in this study. Further, the high proportion of impassable culverts was consistent through time, which suggests that typical stream disturbances have not been a major driver in creating fish passage barriers, especially since all fish passage culverts are required to withstand 100-year flood events. We found no evidence of large-scale flood events that could explain the failure rate over the large geographic extent of the study. We suggest that culvert failure rates are related to permit process shortcomings and poor quality control during culvert installation rather than the results of disturbances that occur postconstruction.

The culvert designs used in this study are similar to or the same as many employed throughout North America (Hotchkiss and Frei 2007). Our study did not address the adequacy of culvert design types per se. However, the number of no-slope culverts that failed to meet the fish passage barrier standard in our study suggests that greater scrutiny of the no-slope design type and applicable stream conditions is warranted. Likewise, the number of “unknown” or “hybrid” culvert design types that resulted in fish passage barriers suggests that deviation from established design types should be avoided or that greater engineering review is needed for these structures with respect to on-site stream conditions.

The implications of this study are somewhat unclear. Although we know which design types are most likely to become fish passage barriers and the proximal cause of those failures (i.e., particular substandard design criteria), we do not know what process led to those failures. Nonetheless, based on our experience we can offer some reasonable measures to improve the performance of fish passage programs. Currently, WDFW biologists receive little initial or ongoing training in fish passage assessment or stream geomorphology associated with fish passage restoration. Training, like monitoring, is often sacrificed in times of lean budgets. Given the costs of fish passage structures and high failure rates observed in this and other studies (Langill and Zamora 2002; Gibson et al. 2005; Quinn et al. 2007), we suggest that training become a regular part of all programs aimed at providing fish passage. At a minimum, this training should include applied aspects of stream geomorphology and hydrology and culvert design. We also conclude that greater field effort by permitting biologists is necessary. This field time should be spent assessing preconstruction stream conditions and compliance conditions immediately after construction but before construction equipment is moved from the site (i.e., “as-built” compliance). As-built compliance inspections would limit the cost associated with moving heavy construction equipment. Finally, there is a critical need for compliance and effectiveness monitoring.

Despite the call for ongoing compliance and effectiveness monitoring of fish passage restoration, most of our knowledge of restoration failures comes from individual case studies (Roni et al. 2002; Pess et al. 2003, 2005; this study). Given the substantial investment of public and private dollars to recover salmon and the importance of providing fish passage in meeting conservation and recovery goals, policy makers should provide better mechanisms to ensure compliance from project sponsors and improve the process by which they evaluate the proposed plans in the context of project site conditions.

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