Implementation and Effectiveness Monitoring of Hydraulic Projects

Year-Five Progress Report

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Table of Contents

Executive Summary

Purpose

WDFW is monitoring its hydraulic project approval (HPA) process to help ensure that hydraulic structures comply with current rules and that current rules effectively protect fish life. Monitoring provides feedback that should allow us to continually improve the HPA process. Because two parties are involved in hydraulic projects – WDFW (the permittor) and the permittee, the success of project implementation depends on the performance of both parties. Hence, we collect information that should allow us to improve the performance of both WDFW and the permittee.

This report covers: 1) implementation monitoring of culverts; 2) implementation monitoring of marine shoreline armoring; and 3) effectiveness monitoring of culverts.

Implementation Monitoring of Culverts

Successful implementation of an HPA permit for a culvert occurs when: 1) the issued permit or project plans include specifications for the five critical structural dimensions – culvert width, length, culvert slope, minimum countersink at the outlet, and maximum countersink at the inlet; 2) specifications conform to Hydraulic Code Rules[1] and/or follows WDFW's design guidelines; and 3) the completed structure complies with its permit.

Overview

For 5 years from 2013 to 2017, we evaluated implementation of 263 new and replacement culverts in western Washington, an average of 53 culverts/year. The 263 culverts corresponded to 209 HPA permits because many permits covered two or more culverts. About half (49%) of the culverts were stream simulation design, 27% were no-slope design, and 21% were of unknown design.

Permit Compliance Rates for Culvert Structural Dimensions

We calculated compliance rates for each structural dimension (Table E1). Compliance was best for culvert slope (82%) and worst for minimum countersink (40%). When we applied a compliance tolerance, slope had 93% compliance and minimum countersink had 60% compliance. We discuss the issue of compliance tolerances below. Compliance for culvert slope exhibited a statistically significant positive trend from 77% in 2013 to 87% in 2017.

[1] In July 2015, WDFW instituted revised hydraulic code rules. Unless noted otherwise, references to the hydraulic code rules in this report refer to the rules in effect after July 2015.

Table E1. The average compliance rates (percent of culverts) for culverts from 2013 to 2017. Only culverts that had structural dimension specified on permit or plans could be included in this calculation. We had only 3 years of data (2015-2017) for culvert countersink. We did not apply compliance tolerances to columns titled worst and best years.

		Percent of Culverts Compliant			
Structural Dimension	**Number of Culverts**	**No Tolerance**	**With Tolerance***	**Worst (year)**	**Best (year)**
width at streambed	186	60	81	31 (2014)	83 (2016)
length	248	47	92	44 (2017)	49 (2016)
slope	238	82†	93	77 (2013)	87 (2017)
minimum countersink	98	40	60	34 (2016)	45 (2015)
maximum countersink	96	69	82	67 (2016)	70 (2017)

† applied ±1% engineering tolerance recommended by Barnard et al. (2013).
* Compliance tolerances for each dimension were: width = +5% of permitted width; length = -5% of permitted length, slope = permitted slope ± 2%, minimum countersink = -5% of culvert rise, maximum countersink = +5% of culvert rise.

HPA Permit Quality

An HPA permit is complete when it has all critical structural dimensions on the permit or in the project's plans. For 5 years from 2014 to 2017, we found an average of 89% of critical structural dimensions per year in permits or project plans (Table E2); the minimum of 86% occurred in 2015. Over 90% of permits or plans specified culvert slope, length, and minimum countersink. Culvert design type was missing from 20% of permits or plans, but the percentage improved over time.

Table E2. Percent of permits or plans with specification for culvert dimensions.

Culvert Dimension	**All Years**	**Worst (year)**	**Best (year)**
design type	80	72 (2015)	97 (2017)
width at streambed	83	76 (2015)	87 (2016)
slope	93	91 (2017)	96 (2016)
minimum countersink	91	88 (2017)	92 (2016)
maximum countersink	83	74 (2015)	88 (2017)
length ↑	97	94 (2014)	100 (2017)
all combined	**89**	**86 (2015)**	**92 (2016)**
total number of culverts	209		

↑ denotes of statistically significant positive trend.

In July 2015, habitat biologists were asked to include provisions for all five culvert structural dimensions in HPA permits. We found that after 2015, the percentage of permits containing provisions for culvert width, length, and maximum countersink increased substantially. Nevertheless, in 2017, only 29% of the permits contained provisions for all critical structural dimensions.

Other positive trends in permit quality include: the average number of provision per permit for critical structural dimension increased from 1.9 to 3.1 (out of 5); and the percent of permits with provisions for all critical structural dimensions increased from 0% to 29% per year. Finally, permit provisions (including project plans) conforming with rules or guidelines increased from 85% in 2015 to 95% in 2017.

Fish Passage Barrier Assessment of New Culverts

We conducted Level A and Level B barrier assessments on new and replacement culverts and found that 11 (4%) of 263 new culverts constructed between 2013 and 2017 were fish passages barriers. In addition, the percentage of culvert passing Level A and B increased from 81% in 2013 to 94% in 2017, a substantial improvement over the findings of Price at al. (2010) who found that 25% (5 of 20) 1 to 2-year old culverts were fish passage barriers.

Major Issues Identified through Monitoring of Culverts

Low Compliance Rates for Culvert Countersink

Over three years of monitoring, only 40% of culverts met permit provisions for countersink. A 5% compliance tolerance increases that percentage to 60%. A number of factors may have contributed to this low success rate. First, the Habitat Program has two different ways to measure culvert countersink – one used by the Fish Passage Barrier Inventory Section and one used by the Engineering Section. Further, WDFW's Water Crossing Design Guidelines do not explain how to measure countersink, nor do we know how HPA permittees measure countersink. It may be that permittees (or their contractors) measure countersink differently than WDFW, which could explain why some culverts did not meet the permit specification for countersink.

The second factor may be related to the time between completion of culvert construction and implementation monitoring, which was typically about 1 month (range 1-3 months). During that time, we expect some sediment to be mobilized after water is allowed to flow through a new culvert that could result in erosion of the streambed within the culvert. As a result, the streambed's minimum elevation could be lowered, and culvert countersink could be reduced.

The third factor is the lack of information provided by the Water Crossing Design Guidelines on the shape of a culvert's streambed. Sometimes a thalweg (or a low flow channel) is built into the initial streambed shape during culvert construction. This is WDFW's preferred streambed shape, however the Design Guidelines are silent on this issue. Consequently, sometimes no thalweg is created. Compliance rates could be inflated if a new flat streambed are more susceptible to erosion than a new streambed with a thalweg. Because we do not know the how the initial streambed shape affects future channel shape and the amount of countersink, we are addressing that question through effectiveness monitoring.

Inaccurate Channel Width Estimates could Lead to Undersized Culverts

According to WDFW's Water Crossing Design Guidelines (Barnard et al. 2013, p. 13), bankfull width is by far the most important parameter in culvert design, and thus accurate channel width measurement is important. Channel width estimates by permittees tended to be narrower than estimates of bankfull width we obtained during implementation monitoring. On average, over the 5 years, 59% of estimates per year were narrower; the other 41% were wider than our estimates. When permittees' channel width estimates were narrower, they averaged 28% narrower than our channel width estimates, and this percentage stayed roughly constant over the 5 years of monitoring.

Our data show that contractors are very good at meeting HPA permit provisions (including project plans) for culvert width at the streambed. However, we found evidence that HPA provisions for culvert width at the streambed are sometimes wrong. We calculated an "expected" culvert width using the channel width estimated during monitoring and found that the expected culvert width was wider than the permitted culvert width for 27% of culverts from 2014 to 2017. In addition, when the expected culvert width was wider than the permitted width, it was, on average, 2.4 ft wider and ranged from 2.4 to 8.9 ft per year. On the other hand, we also found evidence that inaccurate channel width estimates by permittees were corrected during the permitting process, that is, culverts were wider than would be expected based on channel width estimates in the permits/plans. We discovered this by comparing a culvert's permitted width with the culvert width based on the permittee's channel width estimate. The permitted culvert width was larger than the culvert width for 83% of culverts based on the permittee's channel width estimate, and permitted culvert widths could be up to 12.6 ft larger than the culvert width based on the permittee's channel width estimate.

We have found discrepancies in channel width estimates between permittees and our monitoring field crew, between permittees and habitat biologists, and between habitat biologists and the monitoring field crew. These discrepancies demonstrate something we are well aware of – 1) some permit applicants do not know how to measure channel width, and 2) repeatable, accurate estimates of channel width are difficult to obtain.

Information Missing from Permit and/or Project Plans

Important culvert information was missing for a substantial proportion of permits and plans. Over the five years of monitoring, design type and channel width were missing for 21% and 41% of culverts, respectively. Furthermore, 11% of permits and plans were missing structural dimensions. We may have missed some of this information in our review based on the fact that much of that information was very difficult to locate amongst the many pages of plans, the JARPA, reports, and other supporting documentation. In addition, every engineering firm (maybe every engineer) seems to do drawings differently, and some are not drawn to scale. These difficulties reduced the efficiency of our monitoring efforts, and we suspect these same difficulties plague habitat biologists as well.

Information Missing from Permit

While staff deserve credit for the improved quality of HPA permits issued for culverts, permit quality can be further improved. Many permits lacked provisions for at least one of the five critical structural dimensions – a shortcoming may be due to communication issues. Prior to July 2015, habitat biologists were not expected to include provisions for all critical culvert dimension. Nevertheless, at that time, many biologists regularly wrote permit provisions for one or more critical culvert dimensions, especially culvert width at stream bed, and a few biologists wrote provisions for all culvert dimensions. Shortly before July 2015, when training for the revised Hydraulic Code Rules occurred, habitat biologists were asked to include provisions on the permit for each critical culvert dimension, and the new HPA permit template included those provisions. However, expectations were apparently unclear. While reviewing this report, two Habitat Program staff from separate regions stated that culvert dimensions in plans should not need to be repeated in permit provisions.

Meaning of Compliance

Does a culvert that is 1 inch longer than its permitted length violate its permit? According to a strict definition of compliance, the answer is yes. If we apply a tolerance for error, then the answer is less clear. We believe that the meaning of "compliance" and how permit compliance should be determined is an unresolved policy issue. Consequently, we did not calculate compliance rates for this report, and, in fact, we avoid the word "compliance. Instead, we calculated statistics that describe permittees' performance relative to their permits, and used phrases like "met the permit provision" or "met the permit's specification" to describe, the quality of culvert construction.

A closely related issue is the application of engineering or "compliance" tolerances in HPA implementation monitoring. A tolerance is the maximum acceptable difference between the actual dimension of a structure and the desired or prescribed value of that dimension. Engineering tolerances take into account the practical limitations that technology imposes on construction and the inexact nature of physical measurements. A compliance tolerance might also take into account the potential impacts of a structure that is built too long, too narrow, or too steep. In other words, compliance tolerances should take in account how accurately a permittee can build a culvert, how accurately the permittor can measure it, and how fish will be affected. Tolerance are difficult to specify a priori, and hence, as we learn more through implementation and effectiveness monitoring, we may develop reasonable tolerances for each of the five critical structural dimensions.

If we apply a strict definition of compliance to culvert length, then over the 5 years of monitoring, at least 53% of culverts were noncompliant because they exceeded the length specified on the permit or project's plans. Under a strict definition of compliance, if a culvert with a permitted length of 50 ft is actually 50.1 ft long, then it is noncompliant. If an engineering or compliance tolerance is applied, then that same culvert is compliant. If we apply a 5% tolerance to the permit specification for length, then only 8% of culverts we monitored were noncompliant for length, and in 2017 no culverts were noncompliant for length. The key question is "when does it matter"? That is, would an extra 1.2 inches on a 50 ft long culvert matter to fish passage or to natural fluvial processes? If not, then should we institute tolerances for culvert structural dimensions?

Recommendations for Culvert HPAs

Provide more and better guidance on culvert countersinking in WDFW's Water Crossing Design Guidelines. Specifically, explain how to properly measure culvert countersink, describe the correct streambed shape within a countersunk culvert, and correct Figure 3.4 in the guidelines.

Challenges with estimating channel width should be addressed by: 1) developing a standard procedure for estimating channel width, 2) training appropriate Habitat Program staff based on the new procedure, and 3) offering a similar training to people outside WDFW. In addition, because bankfull width is by far the most important parameter in culvert design, we recommend that an "official" channel width estimate be recorded for every new culvert in APPS or on the HPA permit.

For the purposes of permitting, rule enforcement, and monitoring, we recommend that key information – such as bankfull width, channel slope, culvert design type, and culvert dimensions – should be recorded and easy to find. For example, a mandatory form that summarizes key information could be submitted with all HPA applications.

Determine the meaning of "compliance" and how permit compliance should be determined for hydraulic projects. Also decide whether engineering or compliance tolerances should be applied when inspecting hydraulic structures.

Implementation Monitoring of Marine Shoreline Armoring

Successful implementation of an HPA permit for marine shoreline armoring occurs when: 1) the issued permit or project plans include the critical structural dimensions, 2) those dimensions conform to Hydraulic Code Rules,[2] and 3) the completed structure complies with its permit. The two critical structural dimensions are armor length and armor location.

Overview

For 3 years from 2014 to 2016, we evaluated implementation of 69 marine shoreline armoring projects (i.e., HPA permits) in Puget Sound, an average of 23 projects per year. Over half (58%) of the projects were for replacement armor (of previously armored shoreline), 32% were for new armor (on previously unarmored shoreline), and 10% were for extension of existing armor footprint.

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[2] In July 2015, WDFW instituted revised hydraulic code rules. Unless noted otherwise, references to the hydraulic code rules in this report refer to the rules in effect after July 2015.

Permit Compliance Rates for Shoreline Armoring Structural Dimensions

We calculated compliance rates for each structural dimension (Table E3). Compliance was higher for armor location (65%) compared to armor length (57%). However, when we applied a 10% compliance tolerance, compliance rates for armor length and location increased to 87% and 83%, respectively. The issues of compliance and tolerances are discussed under culvert monitoring.

Table E3. The average compliance rates (percent of projects) for shoreline armor over the years 2014, 2015, and 2016. Only armor projects that had structural dimensions specified on permit or plans could be included in this calculation. No compliance tolerance applied for worst and best years.

Structural Dimension	Number of Projects	Percent of Projects Compliant			
		No Tolerance	**With Tolerance***	**Worst (year)**	**Best (year)**
armor location	69	65	83	52 (2014)	81 (2016)
armor length	69	57	87	45 (2015)	63 (2016)

* Compliance tolerances for each dimension were 10% of permitted value.

Permit Quality for Marine Shoreline Armor

An HPA permit should have specifications for both critical structural dimension on the permit or in the project's plans. Specifications for both critical structural dimensions were found for 88%, 96%, and 89% of permitted projects in 2014, 2015, and 2016, respectively.

We found armor length was specified in either HPA permit provisions or project plans for 83% (n=57) and 13% (n=9) of projects, respectively. For three projects (4%), armor length was not specified in either HPA permit or plans, and required that we manually measure dimensions on construction plans. In contrast, armor location was specified in HPA permit provisions for 4% (n=3) of projects, on plans for 71% (n=49) of projects, and measured manually from construction plans for 25% (n=17) of projects.

An HPA permit should specify structure location that is consistent with Hydraulic Code Rules (WAC 220-660-370). Across all survey years (2014-2016), 90% (n=62) of HPA permits provided location of armor structure consistent with Code rules.

For projects which identified structure location consistent with Code rules, we found 58% (n=36) on the HPA permits and 42% on project plans. All HPA permits that failed to provide location information consistent with Code rules (n=7) were for new construction.

Permitted Structure Design

Ideally, HPA permit for marine shoreline armor will utilize a structure design consistent with site-specific erosion risk and best management practices. Of 158 HPA-permitted designs for shoreline armor, 71 (45%) were consistent with site-specific recommendations of the Marine Shoreline Design Guidelines (MSDG). Of permitted designs inconsistent with MSDG recommendations, 83 (53%) (n=83) were harder than recommendations (i.e. "over-built"), and 3% (n=4) were softer than recommendations (Table E4).

Table E4. Comparison of HPA-permitted shoreline armor design versus MSDG recommended shoreline armor design. Values are number of permits reviewed, where: > denotes an armoring that was harder than the MSDG recommendation, and < denotes armoring that was softer than MSDG recommendation.

	Year			
Comparison	**2014**	**2015**	**2016**	**Total**
HPA = MSDG	24	28	19	71
HPA > MSDG	58	16	9	83
HPA < MSDG	3	0	1	4
Total	85	44	29	158

Major Issues Identified through Monitoring of Marine Shoreline Armoring

Quality of permit information

Specifications for structure length and location were provided in HPA permit provisions or supporting application material (e.g., construction plans) for 96% and 75% of projects, respectively. For the remaining projects, specifications were not explicitly provided but were obtained by measuring them on the project's construction plans. Consequently, disproportionate effort was required to determine the permitted armor location for 25% of projects that we surveyed.

Most permits contain standard provisions that specify the new armor's location with respect to the ordinary high water line (OHWL) or to pre-existing armor. These provisions are consistent with WAC 220-660-370, however, compliance was sometimes impossible to evaluate because the ordinary high water line or pre-existing structure were obliterated during construction.

Consistency of permit information

For 34 of the 69 projects surveyed, structure location was described both as a distance to a benchmark or reference feature and as an elevation at the structure's base. For 25 of the 34 projects, armor locations based on these two measures differed by more than 10%, and, in fact, there were 8 projects where one measure indicated noncompliance but the other measure indicated compliance.

Site-specific risk assessment and structure design

Permitted designs for marine shoreline armor were often inconsistent with MSDG-recommended designs. We found that the majority of armor structures were permitted and constructed in excess of MSDG recommended armor design. Of the HPA-permitted projects that were inconsistent with MSDG recommended design, the majority were for armor replacement projects with low erosion risk.

Recommendations for Marine Shoreline Armoring HPAs

Numerical values for structure location and length should always be provided on either the permit or the project's plans.

Determination of permitted structure location should be verifiable and repeatable before and after construction. The most reliable determination of shoreline location is distance (either horizontal or slope) from a permanent benchmark.

Encourage habitat biologists to discuss MSDG recommendations with permittees or their contractors. Develop incentives to encourage land owners to follow MSDG recommendations.

Effectiveness Monitoring of Culverts

Effectiveness monitoring is done to determine whether hydraulic projects are yielding the desired habitat conditions through time. For culverts, the desired condition is no net loss of "habitat functions necessary to sustain fish life" and no net loss of "area by habitat type." (WAC 220-660-030(107)).

We believe that a geomorphic approach to culvert design will maintain habitat functions. The geomorphic approach allows stream processes within a culvert, such as the movement of sediment and woody debris, to behave similarly to natural processes occurring upstream and downstream of a culvert. Effectiveness monitoring tracks the continuity of stream process through a culvert and its upstream and downstream reaches by measuring sediment, wood, and various other indicators at through time. .

Common Culvert Problems

The most common problems occur when a culvert is undersized. Undersized culverts create flow restrictions at the culvert inlet that increases velocities through the structure causing downstream scour to occur. This downstream scour and incision can create deep plunge pools below the culvert outlet. Additionally, undersized culverts can create backwatering effects. Slower stream velocities upstream of the culvert will then result in sediment deposition and channel aggradation upstream. These common problems caused by poorly designed culverts influenced our approach to effectiveness monitoring.

Approach to effectiveness monitoring

Effectiveness monitoring collects data to determine changes in channel shape, channel slope, the number of pools, the amount of large wood, and changes in sediment sizes in the culvert vicinity. Through data analysis, we identified "changes of concern" for continued monitoring through time.

Data were collected at new, properly implemented projects (i.e., followed rules and guidelines) each year beginning in 2013, and returning to the same projects at years 2 and 5, with the intention of also returning at years 10 and 20. We have collected effectiveness data at 102 culverts; approximately 20 culverts per year.

Current findings

One year after construction (monitoring year 2), all culverts monitored for effectiveness passed the Level A fish passage barrier assessment. These culverts have undergone changes in channel bed variability, as well as reductions in the abundance of pools and large wood. We attributed these changes to stream readjustments that naturally occur post-construction, and not to culvert effectiveness.

For 11 culverts monitored at 5 years post-construction, we found that the streambed had stabilized and we detected fewer changes of concern for most performance indicators. We will learn more in the next two years (2018-2019) as we collect and analyze more data at culverts constructed 5 years ago.

Part 1. Monitoring of the Hydraulic Project Approval Process

Introduction

One of the main responsibilities of WDFW's Habitat Program is protecting fish life and fish habitats through the administration and enforcement of the Hydraulic Code Rules (Chapter 220-660 Washington Administrative Code). Through these rules, WDFW regulates the construction of hydraulic structures or the performance of other work that will use, divert, obstruct, or change the natural flow or bed of any of the salt or fresh waters of the state. The rules set forth procedures for obtaining a hydraulic project approval (HPA, i.e., a permit), and the rules specify criteria used by WDFW for project review and conditioning HPAs. The purpose of an HPA is to ensure that construction or performance of work is done in a manner that protects fish life (WAC 220-660-010)[3]. Furthermore, the Hydraulic Code Rules reflect the best available science and practices related to the protection of fish life, and WDFW will incorporate new science and technology into the rules as it becomes available (WAC 220-660-020).

The immense importance of the Habitat Program's HPA permit authority was recently highlighted by the "Culvert Case." In 2007, Federal District Judge Ricardo S. Martinez ruled that highway culverts blocking fish passage and owned by Washington State violated treaties with Indian tribes (Blumm and Steadman 2009). In 2013 Judge Martinez also ruled on the remedy – the State must replace all state-owned culverts that block fish passage within areas of western Washington covered by the treaties (Lovaas 2013). Within those areas, hundreds of state-owned culverts block anadromous fish migration to hundreds of miles of fish habitats. The estimated cost for this remedy is over $2.4 billion. State-owned culverts are but a fraction of the thousands of state, county, city, and private culverts that block fish passage. The cost of repairing or replacing these culverts could be tens of billions of dollars. The enormous impact of impassable culverts makes plainly evident the absolute necessity that new hydraulic projects comply with current rules and that current rules be effective at maintaining fish passage.

To help ensure that hydraulic structures (e.g., bridges, culverts, freshwater and marine shoreline armoring) are compliant with current rules and that current rules effectively protect fish life, WDFW is monitoring its HPA process. The main purpose of monitoring is to provide feedback which over time helps us to improve both implementation of the current Hydraulic Code Rules and the effectiveness of those rules at protecting fish life. Specifically, the purpose of monitoring the HPA process is to provide reliable, useful information that describes:

1. opportunities to improve WDFW's process for issuing HPA permits;
2. opportunities to improve compliance by permittees;
3. performance of properly implemented hydraulic structures;
4. opportunities to improve rules or design guidelines so that hydraulic structures cause no net loss of fish habitat area or functions over their expected service life.

This report covers implementation and effectiveness monitoring conducted from 2013 to 2017 (inclusive). We limited the scope of implementation monitoring to new culverts (including replacements) on fish-bearing streams in western Washington and to new and replacement marine shoreline armoring. We limited the scope of effectiveness monitoring to culverts. Only these two types of hydraulic structures were monitored because: 1) they are common types, 2) both have high potential to damage fish habitats, and 3) limitations imposed by funding forced us to concentrate our efforts on only two types of hydraulic

[3] Fish life" means all fish species, including food fish, shellfish, game fish, unclassified fish and shellfish species, and all stages of development of those species (WAC 220-660-030 (55)).

structures. Dionne et al. (2015) describes effectiveness monitoring of marine shoreline armor conducted in 2013 and 2014.

Adaptive Management

Monitoring is essential for adaptive management. Monitoring is part of the feedback loop which provides information for improving management (Figure 1.1). The adaptive management process is a continual cycle consisting of planning, action, monitoring, evaluation, and adjustment (Bormann et al. 1994, Wilhere 2002). As part of the feedback loop, monitoring focuses on regular management operations. The word "monitor" is derived from the Latin word *monēre*, which means to warn. Hence, monitoring provides a "warning" to managers that policies or management practices are not achieving desired outcomes.

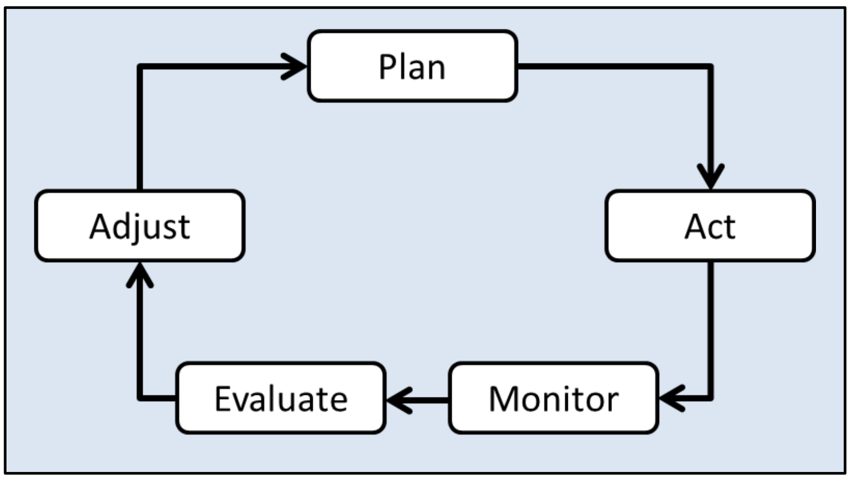

Figure 1.1. The adaptive management cycle (modified from Bormann et al. 1994).

A hierarchy consisting of three types of monitoring – implementation, effectiveness, and validation – has become a common framework for monitoring programs in natural resource management (MacDonald et al. 1991, USDA and USDI 1994). All three types of monitoring provide essential feedback for adaptive management. Implementation monitoring determines whether projects were implemented properly. Implementation monitoring is not compliance monitoring, although the two are related.[4] Compliance monitoring focuses exclusively on the performance of a permittee. Implementation monitoring is broader in scope; it monitors the performance of both the permittee and permittor. Using the information collected through implementation monitoring, the entire regulatory process may be improved to achieve a higher level of compliance.

Effectiveness monitoring is done to determine whether projects are yielding the desired habitat conditions. Effectiveness monitoring compares consequent habitat conditions resulting from a hydraulic project with the desired or expected habitat conditions. Assuming that HPA permits were implemented correctly, repeated failures to achieve desired conditions at multiple sites would suggest that Hydraulic Code Rules or design guidelines are not protecting fish habitats.

[4] The terms "implementation monitoring" and "compliance monitoring" are sometimes considered to be synonymous (Ellefson et al. 2001, DeLuca et al. 2010).

Validation monitoring tests the validity of our assumptions regarding the association of a species to the desired habitat conditions. Validation monitoring usually measures a species' response to habitat conditions produced through management, and it is done to determine whether a particular species responds to the desired habitat conditions as anticipated. Validation monitoring could, for example, test the hypothesis that no-slope culverts pass all life stages of all fish species at times when fish are actively moving up or down streams. Our first five years of HPA monitoring included no validation monitoring.

Our monitoring framework is hierarchical because the results at one level influence the results at lower levels (Figure 1.2). Implementation monitoring, for instance, determines which management activities will be monitored for effectiveness. Only successfully implemented hydraulic projects, as determined through implementation monitoring, become potential subjects of effectiveness monitoring. Limiting effectiveness monitoring in this way makes efficient use of resources allocated to adaptive management. However, both successes and failures provide feedback for improving implementation.

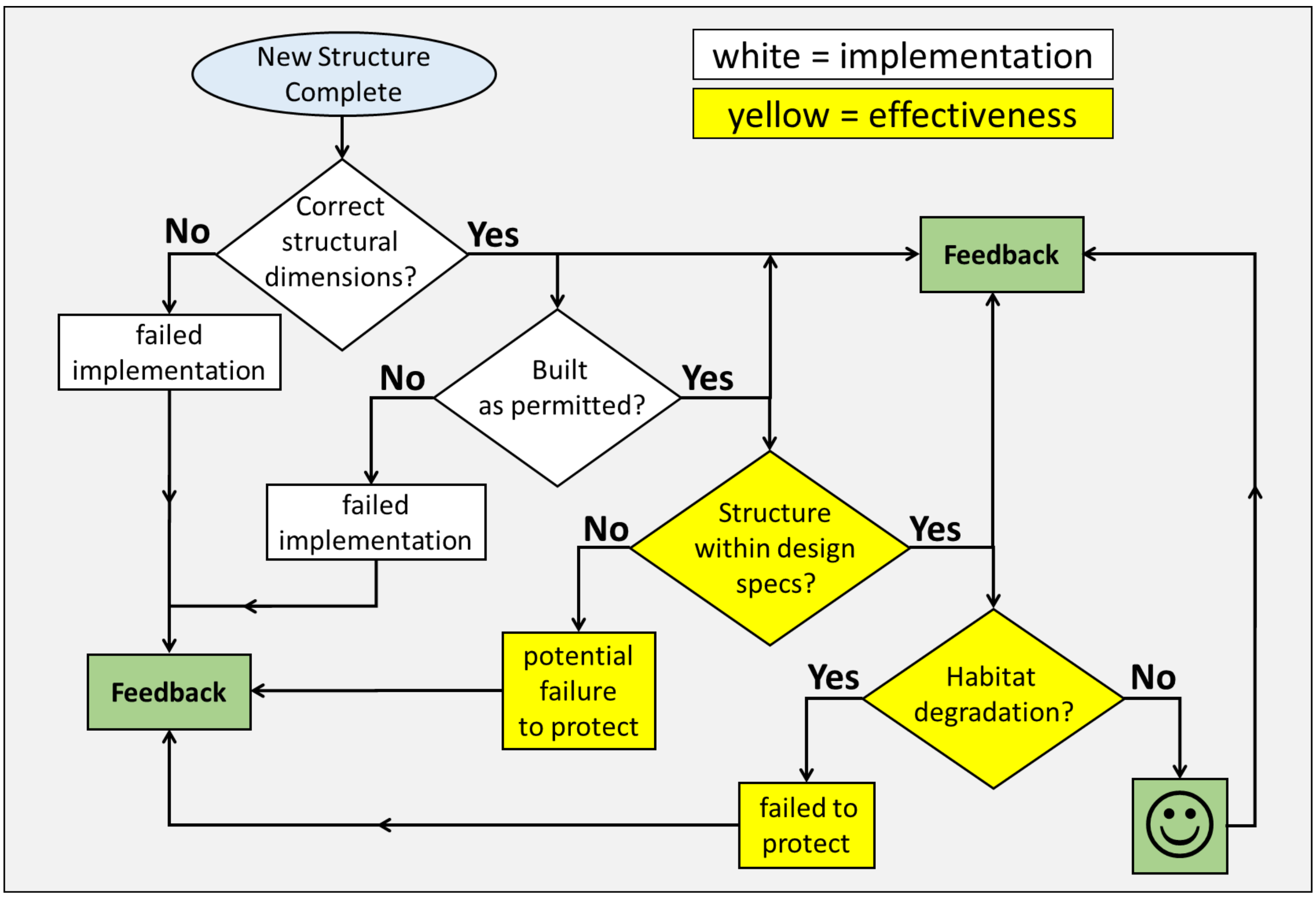

Figure 1.2. Conceptual model depicting relationship between implementation monitoring and effectiveness monitoring of a hydraulic structure. Implementation monitoring occurs once at each hydraulic structure. Effectiveness monitoring occurs many times over time per structure.

Implementation Monitoring

The ultimate purpose of implementation monitoring is improving the implementation of hydraulic projects. Two entities are involved in implementation of a hydraulic project: the permittor (WDFW) and the permittee. The success or failure of project implementation depends on the performance of both entities. Hence, implementation monitoring collects information that could be used to improve the performance of both WDFW and the permittee. Successful implementation of hydraulic projects occurs when the hydraulic structure: 1) fully complies with the permit, and 2) the issued permit contains all necessary information (i.e., permit provisions) and fully accords with the Hydraulic Code Rules[5] and/or follows WDFW's design guidelines (e.g., Barnard et al. 2013).[6]

A successfully implemented hydraulic project must have permittee compliance and permittor accordance. *Compliance* refers only to the permittee's performance relative to the permit. Compliance means the hydraulic structure constructed by the permittee conforms to the HPA permit. Permittee compliance is based strictly on the contents of the permit, even when the permit is incomplete, vague, ambiguous, or contains errors. A common permit provision is "work shall be accomplished per plans and specifications approved by the Washington Department of Fish and Wildlife."[7] This provision generally refers to engineering drawings or plans submitted by the permittee. Hence, compliance often also means compliance with the approved project's plans. *Accordance* refers to the permittor's performance relative to either the Hydraulic Code Rules or design guidelines.[8] For the permittor, accordance means the permit's provisions, including permittee's plans, fully conform to Hydraulic Code Rules or follow WDFW's design guidelines. If a permit's provisions or approved project plans do not accord with rules, then it is possible for a permittee to construct a hydraulic structure that complies with their HPA permit but does not accord with HPA rules.

Through implementation monitoring, we attempted to answer four key questions that pertain to permittor and permittee performance:

1. Did permittors issue complete permits, that is, ones that contain provisions and/or project plans for all critical structural dimensions?
2. Are the permittors' permits accordant with Hydraulic Code Rules?
3. Do the permittors' permits follow the culvert design guidelines
4. Did permittees comply with their permits?

Compliance

For the first 3 years of implementation monitoring, we estimated the annual compliance rate of permittees and submitted that information to Results Washington, a government accountability program started by Governor Inslee (GO 2018). We also reported compliance rates in our first progress report for hydraulic structure monitoring (Wilhere et al. 2015). However, since then, our perspective on compliance has evolved. We now believe that "compliance" is an unresolved policy issue that requires guidance regarding the meaning of compliance and how to determine compliance. Consequently, we did not calculate compliance rates for this report, and, in fact, we avoid the word "compliance." Instead, we characterize differences between critical structural dimensions specified on permits and actual structural

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[5] In July 2015, WDFW instituted revised hydraulic code rules. Unless noted otherwise, references to the hydraulic code rules in this report refer to the rules in effect after July 2015.
[6] The current culvert design guidelines are Barnard et al. (2013), however, all culverts monitored in year one and some culverts in subsequent years were designed prior to 2013, and hence, they may have followed the guidelines of Bates et al. (2003).
[7] "Plans and specifications" refers to material submitted by the applicant in any form. A project may not have engineering drawings or plans of any sort, but relies on a text description of the planned work. Or, a project may rely on photographs that may or may not be annotated with project details. Or, it may have plans of some sort that are augmented with text in the application. However, the vast majority of projects submit engineering drawings or plans.
[8] WDFW cannot legally require HPA applicants to follow a design guideline that is not in the Hydraulic Code Rules. However, prior to July 2015, stream simulation culverts were not in the rules. Consequently, stream simulation culverts permitted before July 2015 were evaluated by comparison to the guidelines.

dimensions measured in the field in an effort to inform discussions about the meaning of "compliance" and how to evaluate it.

Evaluating HPA permit compliance through implementation monitoring raises the following interrelated questions. First, should evaluations of HPA permit compliance incorporate tolerances? In other words, if an HPA permit states that a culvert should be 10 ft wide at the streambed, but the culvert is too narrow by 1 inch, then is that culvert noncompliant? If a 1 inch error is acceptable, then what amount of error is not? 5 inches? 5 percent? Small errors in hydraulic structure construction may not adversely affect fish life under certain conditions, but, at present, we do not know how large an error (if any) might be tolerable for protecting fish life.

A tolerance is the maximum acceptable difference between the actual dimension of a structure and the desired or prescribed value of that dimension. Tolerances take into account the practical limitations that technology imposes on construction, the inexact nature of measurements, and the potential impacts of a structure built too long, too narrow, or too steep. In other words, tolerances should take in account how accurately a permittee can build a hydraulic structure, how accurately the permittor can measure it, and how fish will be affected. Permit compliance (and permit violations) will be sensitive to tolerances, and therefore, tolerances should be realistic, fair, but also ensure that compliant culverts pass fish and maintain habitat.

Many physical measurements associated with hydraulic projects – bankfull width, channel slope, location of ordinary high water– are made in challenging settings or require subjective judgments that result in high inter-observer variability. In other words, such measurements may be inherently inaccurate and imprecise. Compliance judgments should take into account the inexact nature of the measurements associated with the permitting, construction, inspection, and monitoring processes.

We are aware of only one tolerance established by WDFW for hydraulic tolerances. Barnard et al. (2013) provide tolerances for the slope of no-slope culverts. They recommend that a culvert's slope should be no greater than 1%, and that no-slope culverts installed at greater than 2% slope should be considered noncompliant. The former tolerance is an engineering tolerance and the latter is a compliance tolerance.

For Results Washington and our first progress report (Wilhere et al. 2015), we applied a tolerance of ±5% to all critical structural dimensions except slope.[9] Tolerance values are difficult to specify *a priori*, hence, if we decide to incorporate tolerances into future determinations of compliance, then these preliminary tolerances must be revised as we learn more about the capabilities of HPA permittees or their contractors to accurately build hydraulic structures, our own capability to accurately measure important characteristics of hydraulic projects, and the potential consequences of different tolerances for fish habitats and fish life.

The second question deals with a consistent, agency-wide understanding of "compliance." Can compliance rates reported by implementation monitoring accurately reflect the actual compliance rates of permittees? In practice, compliance by a permittees is determined by habitat biologists. If implementation monitoring is to accurately estimate compliance rates, then the meaning of compliance and how it is determined must be the same for implementation monitoring and habitat biologists. That is, the Science Division's compliance determination for hydraulic projects and habitat biologists' compliance judgments for the same projects must be the same. WAC 220-660-480 and WDFW's Policy 5212 equate "not in compliance" with violations of the Hydraulic Code Rules. Does "not in compliance" determined

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[9] Wilhere et al. (2015) applied a compliance tolerance of ±2% to culvert slope because Barnard et al (2013, p. 204) state, "Culverts installed at greater than 2% slope should be considered noncompliant . . ." This was said for no-slope culverts, but we applied this tolerance to stream simulation culverts too.

through implementation monitoring equal an HPA permit violation? If yes, then what type of enforcement action should be initiated.

The third question raised by "compliance" addresses the nature of compliance judgments. Can compliance be determined by objective criteria or should compliance be determined through subjective judgment? Compliance could be based on objective comparisons of a structure's actual dimensions to its permitted dimensions. In other words, if a structure's actual dimensions do not meet the permit's specification, then that structure is noncompliant. However, a strict letter-of-the-law evaluation ignores information that might be relevant to compliance judgments. In other words, compliance could be situational, and therefore, require the expert judgment of a habitat biologist? If compliance is situational, then can the Science Division's quantitative evaluations of compliance match the on-the-ground judgments made by habitat biologists? On the other hand, if compliance should be determined through a strict letter-of-the-law evaluation, then are habitat biologists using objective criteria when they inspect hydraulic structures?

Effectiveness Monitoring

Effectiveness monitoring is done to determine whether hydraulic projects are yielding the desired project outcome or habitat conditions. For hydraulic structures, the desired condition is "no net loss" of fish habitat area and fish habitat functions (WAC 220-660-030(107)). Specifically, no net loss refers to no net loss of "habitat functions necessary to sustain fish life" and no net loss of "area by habitat type." (220-660-030(107)). For culverts and other water crossing structures, habitat functions necessary to sustain fish life include "[allowing] fish to move freely through them at all flows when fish are expected to move" and "[retaining] upstream and downstream connection in order to maintain expected channel processes. These processes include the movement and distribution of wood and sediment and shifting channel patterns." (220-660-190(2)).

Effectiveness monitoring is currently focused on culverts because we still have important questions about culvert design and behavior. WDFW is recognized as a national leader in culvert design. In fact, according to Cenderelli et al. (2011), "The concept of stream simulation was first introduced by the Washington Department of Fish and Wildlife in 1999." Furthermore, stream simulation is regarded as a major conceptual breakthrough in the design of fish-friendly culverts. However, the limitations and minimum dimensions of the stream simulation design were mostly based on expert judgments. The current design may be robust, but we do not yet know how stream simulation culverts will behave in different settings or over the long term.

Effectiveness monitoring of marine shoreline armor is equally important because the impacts of shoreline armor to nearshore habitats are still poorly understood. Limited resources have forced WDFW to focus on culverts, but our intent is to revive effectiveness monitoring of marine shoreline armor (see Dionne et al. 2015) when funds become available.

Ideally, effectiveness monitoring would determine whether a properly implemented hydraulic project has caused a net loss of fish habitats. Hydraulic projects, such as culverts and shoreline bulkheads, may have adverse effects on fish habitats at the project site or immediately downstream or upstream (or downdrift and updrift) of the permitted structure. Certain culverts, for instance, may pass fish but at high flows cause downstream channel scour or upstream fine sediment deposition both of which degrade fish habitats. Due to natural variability in the physical structure of stream channels and beaches, and the consequent natural variability in fish habitats as well, determining whether a hydraulic structure caused a net loss of fish habitat is technically challenging because changes to habitats in the immediate vicinity of a hydraulic structure may: 1) not be caused by the structure, and 2) not constitute a net loss of habitat.

The main technical challenge faced by effectiveness monitoring is distinguishing habitat changes caused by permitted hydraulic structures from habitat changes caused by other factors. These other factors include natural variability of stream channels or marine beaches, natural catastrophic events, the effects of upstream or updrift land use changes, or long-term climate trends. Confounding factors such as these are particularly acute in aquatic ecosystems. Our task is analogous to a radio receiver. Change caused by a hydraulic structure is a "signal" and changes caused by all other factors are "noise." The challenge is to detect and accurately differentiate a signal broadcast in an extremely noisy environment. Three tactics to increase separation of signal from noise are: 1) monitoring multiple annual groups of hydraulic projects (i.e., multiple cohorts), 2) monitoring a large number of individual projects within each group, and 3) long-term monitoring of every project.

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Part 2. Implementation Monitoring of Culverts

Introduction

HPA implementation monitoring targeted culverts for study because culverts are one of the most common hydraulic structures permitted by WDFW and poorly constructed culverts can have major adverse impacts on fish populations.

Implementation monitoring focused on the five critical structural dimensions of a culvert: width at stream bed, length, slope, countersink depth at outlet, and countersink depth at inlet. We refer to them as "critical" because they are the only culvert dimensions for which minimum (or maximum) specifications are given in the Hydraulic Code Rules (Box 2.1).

Because of limited resources and staff time, implementation monitoring of culverts did not cover all provisions occurring on HPA permits. Implementation monitoring focused on those provisions that can: 1) be evaluated post-construction; 2) be quantitatively measured, and hence, do not require the specialized expertise of a habitat biologist; and 3) require only one site visit. For instance, provisions related to construction timing or equipment were not evaluated because they cannot be reliably evaluated post-construction, and provisions related to re-vegetation or mitigation were not evaluated because they require either a subjective expert judgment or multiple site visits. Furthermore, implementation monitoring focused on the hydraulic structure because relative to other activities regulated under the HPA permit (e.g., re-vegetation), the culvert has the greatest potential to adversely impact fish habitats and is the principal impact being regulated.

Box 2.1. Specifications for Critical Structural Dimensions in WAC 220-660-190(6)

(a) Stream Simulation Design

- width of the channel-bed inside the culvert at the elevation of the stream bed can be determined in one of two ways: 1) approved methodology, 2) approved alternate plan*
- culvert must be set at the same gradient as the prevailing stream gradient*
- countersunk a minimum of thirty percent*
- countersunk a maximum of fifty percent, but not less than two feet*

(b) No-slope Design

- length must not exceed seventy-five feet*
- culvert is installed at a zero gradient
- width of the channel-bed inside the culvert at the elevation of the stream bed must be equal to or greater than the average channel bed width
- countersunk a minimum of twenty percent at the culvert outlet
- countersunk a maximum of forty-percent of at the culvert inlet*

* New rule that went into effect on July 1, 2015.

During our five years of implementation monitoring (2013 to 2017), we were effected by two major changes to the Hydraulic Code and the permitting process. First, on April 11, 2013 the Washington Department of Natural Resources assumed responsibility for regulating hydraulic projects associated with forest practices. After that date, the number of culverts permitted by WDFW decreased substantially.

Second, new Hydraulic Code Rules went into effect on July 1, 2015. The new rules included several rules that affected culvert design (Box 2.1), however, all the new rules for culverts were already recommendations in WDFW's Water Crossing Design Guidelines (Barnard et al. 2013), and hence, the effects were not significant.

Methods

Implementation monitoring of culverts was done in years 2013 through 2017. In most years, the field staff consisted of one biologist who oversaw two technicians. Monitoring was limited to western Washington (Table A-1), i.e., west of the Cascade Crest, because the majority of new culverts built each year are in western Washington, and the size of the study was constrained by available staff. Nevertheless, in most years we believe we were able to collect data on nearly every new culvert (including replacements) in western Washington that was not associated with forest practices. In other words, the scope of our study was all new culverts (including replacements) in western Washington constructed in the years 2013 to 2017. The size of that culvert population declined substantially after April 11, 2013 when the Washington Department of Natural Resources assumed responsibility for regulating hydraulic projects associated with forest practices. However, prior to that date, WDFW issued permits for some culverts associated with forest practices that were built in 2014 or 2015. Beginning in 2016, we monitored no new culverts associated with forest practices.

Our "sampling scheme" for culvert selection was opportunistic – we visited culverts as their availability became known to us, and, when a culvert was on private land, we were granted permission to enter the property. We did not randomly draw from the population of all new culverts in western Washington, however, we believe that we were able to monitor nearly all new culverts in western Washington for which WDFW issued an HPA, especially in 2014 through 2016. Hence, for 2014 through 2016, each year's monitoring effort is thought to be census of culverts, with the exception of a few culverts that we could not visit due to denials by land owners. Because we were able to collect implementation monitoring data from nearly all members of the population, statistical inference regarding a larger population is unnecessary. In other words, our statistics nearly approach actual population parameters without sampling error. Due to reduced funding, monitoring in 2017 cannot be considered a census because we did not visit all newly constructed culverts that we knew of.

The logistics of data collection consisted of five phases. First, because HPA permits are valid for a maximum of 5 years after their issuance date, each year the HPA database was queried for permits issued in the preceding five years. In 2013 and 2014 the HPA database was the Hydraulic Permit Management System (HPMS), but in 2014 the agency switched to a new HPA database known as Aquatic Protection Permitting System (APPS). From the database query, we created a list of permitted culverts that could be built during that year. The plurality of permits on that list were less than 1 year old, but permits 1 to 3 years old were also common (Table A-4).

The second phase, usually done in June and July, entailed contacting all permittees on that list. During that initial contact, we determined whether the culvert would be constructed that year, an approximate date for when culvert construction would be complete, and how further communications with the permittee should be conducted. If the culvert was on private land, then we also requested permission to conduct monitoring activities on the permittee's property. Permission was denied for only a few culverts, mostly in 2013. Implicit denials occurred when landowners ceased replying to our telephone messages or e-mails.

Third, throughout the field season we contacted permittees to get an update on the expected date of completion. Fourth, after the permittee indicated that the culvert was completed, a field crew was scheduled to visit that culvert. The beginning of the field season was determined by in-water work windows (WAC 220-660-110), which are incorporated into HPA permits. The end of the field season was usually determined by winter weather. Hence, the field season began in July and ran to roughly the end of December (Table A-2) when stream flows increased significantly and culverts could not be measured reliably or safely. Our goal was to measure culvert dimensions as soon as possible after construction because the shape of a "rewatered" channel (i.e., slope, width, and thalweg[10] depth) can change rapidly. The time between the end of culvert construction and implementation monitoring ranged from about 1 week to 3 months but was typically about 1 month. The fifth phase of implementation monitoring was traveling to the culvert and measuring the culvert and stream channel.

Data Collection

Data collection consisted of 3 major steps: (1) recording information from the permit and project plans, (2) measurements at the project site, and (3) data entry

Information from Permits. We evaluated the permittor's performance through the issued HPA permit. A permit should be complete and accordant. That is, the permit (including project plans) should specify dimensions for all critical structural dimensions, and those dimensions should agree with Hydraulic Code Rules or design guidelines (e.g., Barnard et al. 2013).[11] We evaluate a permittee's performance through the completed hydraulic structure. That is, we compare the completed culvert with its HPA permit's provisions. The first step of these evaluations is finding permit provisions for the five critical structural dimensions (Box 2.2) and recording the dimensions specified in those provisions.

A common permit provision is "work shall be accomplished per plans and specifications approved by the Washington Department of Fish and Wildlife." This provision refers to engineering drawings or plans submitted by the permittee.[12] Hence, many of the critical dimensions are often not explicitly stated in the permit per se but are contained in the associated engineering drawings or plans. In some cases, critical dimensions were not stated in the either permit provisions or plans. In the first two years of monitoring (2013 and 2014), we estimated missing culvert dimensions by manually measuring a project's engineering drawings/plans. However, in later years, we realized that plans were not reliably drawn to scale, even when they appeared to be. Consequently, after 2014, we did not attempt manual estimates from plans, and culverts with missing dimensions were excluded from analyses that required those culvert dimensions they lacked.

Box 2.2. Key Measurements for Implementation Monitoring

Site Characteristics
- bankfull width
- channel slope

Critical Structural Dimensions
- culvert width at streambed
- culvert slope
- countersunk depth at outlet
- countersunk depth at inlet
- culvert length

Ideally, culvert design type (e.g., stream simulation or no-slope) should be stated on an HPA permit, however, this information is not currently required on permits. Nevertheless, we searched for this information on permits and associated documents in the following order: HPA permit, approved project

[10] A thalweg is the lowest elevation of a stream or river bed. It is mapped as a line drawn to join the lowest points along the entire length of a streambed.

[11] WDFW cannot legally require HPA applicants to follow a design guideline that is not in the Hydraulic Code Rules. However, prior to July 2015, stream simulation culverts were not in the rules. Consequently, stream simulation culverts permitted before July 2015 were evaluated by comparison to the guidelines.

[12] Because a common permit provision refers to approved project plans, unless stated otherwise, reference to specifications for critical structural dimensions on HPA permits or in permit provisions also includes specifications for the critical dimensions on project plans.

plans/engineering drawings, Joint Aquatic Resource Permits Application (JARPA), and various other materials, and stopped searching for design type in other documents once it was found.

WDFW's Water Crossing Design Guidelines state, "The bankfull width [or channel width] is by far the most important parameter in culvert design, therefore accurately measuring it is critical for a successful project." (Barnard et al. 2013, p. 13). Consequently, we were interested in channel width estimates submitted to WDFW by permittees. We searched the aforementioned documents to find channel width estimates.

Measurements at Project Site. At the project site, we measured the five critical culvert dimensions, channel slope, and bankfull width. All data types collected for each culvert are shown on the monitoring data form in Appendix C. Many of the measurements made for implementation monitoring are the same or very similar to those done for fish passage barrier assessment (WDFW 2009). Hence, the methods or procedures used for monitoring were often the same as those used for WDFW's fish passage barrier inventory, but with one exception – culvert countersink.

In the first year of monitoring, we measured culvert countersink with the method used for fish passage barrier assessment. This entails forcing the tip of a gravel probe (a thin, rigid metal rod) down through a streambed's sediments until it reaches the bottom of the culvert. This results in a measurement of sediment thickness at a culvert's outlet or inlet. For fish passage barrier assessment, countersink is always measured at a culvert's invert,[13] regardless of thalweg location (Figure 2.1). Over the second and third years of monitoring, our method of measuring culvert countersink evolved. We found, that our original method was not the best measure of culvert countersink because the channel thalweg (i.e., the lowest part of the stream channel) is sometimes not in the center of the culvert. Consequently, we moved the countersink measurement to the channel thalweg. In 2015, we learned that this countersink measurement is not how the Habitat Program's engineers measure countersink. The engineers define countersink as the difference between the streambed's elevation at the channel thalweg and the elevation of the culvert's invert. We believe that the engineer's definition of countersink is the best definition, and hence, used that definition in 2015, 2016, and 2017 for culvert monitoring.

We became aware of the engineer's method for measuring countersink early in the 2015 field season and were able to revisit culverts where countersink was measured using one of the other methods. The data collected at many culverts during the 2014 field season included measurements with which to calculate the correct culvert countersink depth for some culverts. Using geometric relationships we could calculate the countersink depth for circular (i.e., round) and elliptical culverts. For squash culverts only rough estimates of countersink depth could be determined. The countersink measurement problem of 2014 does not affect rectangular box culverts.

In 2013 and 2014, culvert countersink was determined by measuring the depth of sediments with a gravel probe. In all subsequent years, countersink was measured indirectly by determining the elevations of the channel thalweg and culvert invert. Elevations were determined by setting up a rotary laser level on-site and attaching a laser detector to a stadia rod. The base of the stadia rod was placed on the streambed at the thalweg and on top of a gravel probe at the culvert invert to determine the thalweg and invert elevations respectively. Culvert slope was measured by determining the elevations of the culvert invert at the culvert's inlet and outlet, determining the difference between those elevations, and then dividing that difference by the culvert's length. Culvert length was measured with either a tape or laser rangefinder. Culvert width was measured with either a tape or a stadia rod held horizontally.

[13] The invert is the lowest part on a culvert. For round (i.e., circular), elliptical, and squash culverts the invert is at the center of the pipe's transverse cross-section.

Channel slope and bankfull width were measured upstream and downstream of the culvert in representative reaches outside the influence of culvert construction. Channel slope was measured by determining elevations of the streambed thalweg at two points 15 m apart. Whenever practical a rotary laser level and laser detector were used to determine elevations, otherwise a laser rangefinder was used. Bankfull width was estimated by measuring bankfull width at two places approximately 15 m apart upstream of the culvert, and at two places approximately 15 m apart downstream of the culvert, and averaging the four measurements. Data were also collected for fish passage barrier assessment (WDFW 2009). Level A assessment was done in all five years, and, if needed, Level B assessment was done in years 2014 through 2017.

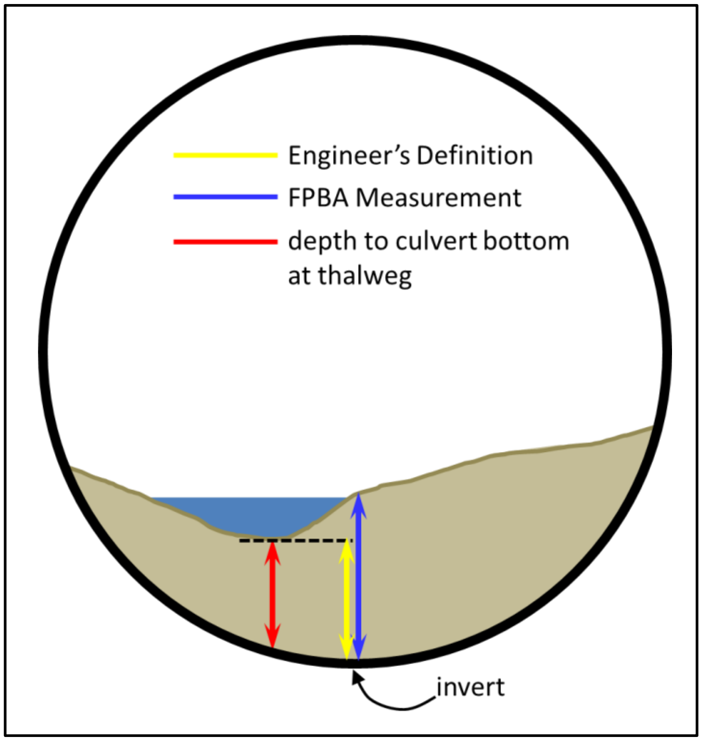

Figure 2.1. Different ways to measure culvert countersink. The Fish Passage Barrier Assessment (FPBA) always measures the countersink depth at the culvert's invert (blue line). The FPBA method was used in year 1 of implementation monitoring. In year 2, culvert countersink was always measured at the channel's thalweg (red line). In subsequent years, the engineer's method was used – i.e., the difference between the thalweg's elevation and the invert's elevation (yellow line).

Data Entry. All data, both collected from HPA permits and collected at culvert site, were transferred from paper data forms to Microsoft Excel spreadsheets (one file per year). Results of fish passage barrier assessments were entered into the Fish Passage and Diversion Screening Inventory (FPDSI) database.

Data Analyses

Data analyses for implementation monitoring were done in Excel and with R (RCT 2013).

HPA Permit Quality. We tabulated culvert design types and the primary source of that information for each year. For each year, we also tabulated the primary source (e.g., project plans, JARPA) of channel width information, the type of channel width that was measured (e.g., bankfull width, width at ordinary high water), and calculated the percent of culvert projects that submitted an estimate of channel width to WDFW. We evaluated the accuracy of channel width estimates by HPA permittees by comparing their estimates to channel width estimates done with data collected during implementation monitoring.

In 2014 through 2017, we recorded presence/absence of provisions for each critical structural dimension in every culvert permit and its associated documents. We also evaluated the provisions' accordance with Hydraulic Code Rules or culvert design guidelines. For each year and each critical structural dimension, we calculated the percent of permits that had a provision for that culvert dimension in the permit and the percent of permits that had a specification for that culvert dimension in the approved project's plans. Permits from 2013 were excluded from the analysis because in that year we did not record the presence/absence of critical structural dimensions in project plans.

Each culvert design type has its own set of rules or design guidelines, and hence, accordance is relative to design type. We encountered four culvert design types: no-slope, stream simulation, hydraulic, and alternate plan. Design type was unknown for some culverts. Bottomless (i.e., arch)[14], culverts could be no-slope, stream simulation, alternate plan, or unknown design. Accordance with rules or design guidelines is difficult to determine when culvert design type is alternate plan, hydraulic, or unknown, and hence, we did not determine accordance for these three design types.

When evaluating accordance rates for no-slope culverts, we compared the dimensions of each culvert against the specifications in WAC 220-110-070(3)(b)(i) for permits issued under the old rules and WAC 220-660-190(6)(b) for permits issued under the new rules. For no-slope culverts we also examined whether a no-slope design was appropriate for the site. WAC 220-660-190(6)(b) states, "The stream channel in which a no-slope culvert will be placed must generally have a channel bed width that is ten feet or less and a gradient less than three percent. However, in some site-specific situations the department may approve no-slope in channels with a gradient up to five percent." These guidelines were incorporated into the Hydraulic Code Rules in 2015 (WAC 220-660-190(6)(b)(i)). We compared channel characteristics measured by the implementation monitoring field crew against this rule.

The old rules do not provide specifications for stream simulation culverts, and therefore, we compared stream simulation culverts permitted under the old rules with the recommendations in Barnard et al. (2013). However, we assumed that minimum countersink referred to the outlet and maximum countersink referred to the inlet. The new rules for stream simulation culverts (WAC 220-660-190(6)(a)) specify the slope and countersinking but do not specify the culvert's width. Instead, the rules state, "The width of the channel-bed inside a stream simulation culvert at the elevation of the stream bed can be determined in one of two ways: (A) The bed width may be calculated by using any published stream simulation design methodology approved by the department. (B) The bed width of an individual culvert may be determined on a case-by-case basis with an approved alternative plan . . ." We encountered no permits for stream simulation culverts that stated which approved methodology was used to determine culvert width, and hence, we assumed that the widths of stream simulation culverts were based on the methodology of Barnard et al. (2013).

<u>Quality of Hydraulic Structure Construction</u>. For the first 3 years of implementation monitoring, we calculated the annual compliance rate of permittees and submitted that information to Results Washington, a government accountability program started by Governor Inslee (GO 2018). However, since then, our perspective on compliance has evolved. We now believe that "compliance" is an unresolved policy issue that demands guidance regarding the meaning of compliance, how to evaluate

[14] Current conventions refer to "bottomless" culverts as "arched" culverts regardless of shape (i.e., rectangular or a true arch).

compliance, and how to incorporate tolerances into compliance/non-compliance decisions. Consequently, we did not calculate compliance rates for this report, and, in fact, we avoid the word "compliance." See further discussion of this issue in the introduction to this report.

Because we lack guidance on the meaning of HPA permit compliance we cannot determine whether a culvert complies with its permit. Rather than determine compliance of each culvert with its permit, we calculated statistics that describe permittees' performance relative to their permits. We calculated the percent of culverts per year that did not strictly meet specifications stated on the permit or approved plans (e.g., culverts that were too narrow or too long relative to the permitted dimensions). We also calculated the mean percent difference between the permitted dimensions and the actual constructed dimensions. Only those culverts that exceeded their specified dimensions were included in that calculation. That is, only culverts with widths too narrow, lengths too long,[15] maximum countersinks too deep, or minimum countersinks too shallow were included in calculation of the mean difference.

For culvert width and length, the difference between permitted dimensions and the actual dimensions is expressed as percent difference.[16] Countersink is calculated as a percentage of culvert height (or rise), but percent difference of a percentage is difficult to interpret. Hence, we chose to express the difference between permitted countersink and actual countersink as a simple difference between them. Slope is also expressed as a percent,[17] and hence, we chose to express the difference between permitted slope and actual slope as a simple difference too.

The comparison of permitted slope to actual slope was handled differently than the other critical structural dimensions for two reasons. First, culvert slope is the only critical structural dimension with an engineering tolerance in Barnard et al. (2013). Barnard et al. (2013, p. 204) suggest an engineering tolerance of ±1% for no-slope culverts, and we applied that same tolerance to stream simulation culverts too. Second, because a culvert slope can be either too steep or too gentle, both were included when calculating the mean absolute difference between permitted and actual slope.

For some of our analyses we applied hypothetical "compliance" tolerances to the permitted structural dimension. For culvert width and length, the tolerance was applied as a percentage of the permitted dimension. A 10% tolerance applied to a permitted culvert width of 8 ft, means that the actual culvert width could be between 7.2 and 8 ft. For culvert slope and countersink, the tolerance was added to the permitted dimension. A 5% tolerance applied to a minimum countersink of 30%, means that the actual culvert countersink could be between 25% and 30%.

For every year and each of the five critical structural dimensions, we created graphs that show the percent difference (culvert width, length,) or difference in real units (culvert slope, countersink) between the permitted dimension and the actual constructed dimension. The graphs include "tolerance contours" that show the range of structural dimensions that fall within different tolerances.

We wanted to know whether the quality of a permit would affect the quality of the constructed culvert. That is, we wanted to know whether the presence of an explicit[18] provision for a structural dimension would affect the percentage of culverts that met permit specifications (on the permit or approved plans)

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[15] Permit provisions typically state: "The length of the water crossing structure must not exceed ___ feet."

[16] % difference = (actual - permitted)/ permitted • 100.

[17] % slope = rise/run * 100.

[18] By *explicit provision* we mean a provision that plainly states the required size (width, length, depth, slope) of a culvert structural dimension rather than referring to specifications on approved plans.

for that structural dimension. To examine that relationship, for each year except 2013 and for each culvert dimension, we compared the difference between the permitted dimension (on the permit or approved plans) and the actual constructed dimension for culverts *with* and *without* an explicit provision for that dimension. For each year, we calculated the mean difference between the permitted dimension and the actual constructed dimension only for those culverts that did not meet the specification stated on the permit or approved plans (e.g., culverts that were too narrow relative to the permit's specified width) both for culverts with and culverts without an explicit provision for a particular structural dimension,. We also compared the percent of culverts *with* an explicit provision that did not satisfy the provision versus the percent of culverts *without* a provision for a structural dimension that did not satisfy the specification on the approved plans.

We have five years of data, so we would like to know if we have observed any significant trends over that time period. Our data were not collected through a random sample. In most years (2014 to 2016), data collection was, or nearly was, a census of new culverts, but in 2017, due to reduced funding, data collection was an opportunistic sample. Consequently, our data do not satisfy the standard assumptions of statistical tests used to detect trends (Zar 1996, p. 325). Fortunately, randomization methods (also known as permutation methods) enable statistical tests on data that were not randomly sampled or violate other assumptions required by parametric tests (Ludbrook and Dudley 1998, Ernst 2004, Howell 2010).

The null hypothesis (H_0) is the slope of the trend equals 0. A *p* value is the probability of obtaining the observed trend if the null hypothesis is true. If the *p* value exceeds a subjective level of significance (e.g., $p < 0.05$), then we reject H_0 and declare the trend to be significant. A "statistically significant" trend is unlikely due to chance events. That is, the trend is likely due to a process, although the process cannot be identified. Because our data were not obtained from a larger population through a random sample, our inferences from randomization tests are limited to the individuals that comprise our study (Ernst 2004). However, logical inferences (rather than statistical) might be made to larger populations with similar characteristics (Ludbrook and Dudley 1998).

We used randomization methods to test for statistically significant trends over time in several statistics: 1) the percent of permits with provisions for each structural dimension, 2) the percent of permits (including plans) with specifications for each structural dimension , 3) the mean number of missing specifications in both permits and plans for each structural dimension, 4) the percent of culverts that did not follow no-slope culvert guidelines for channel characteristics, 5) the percent of permits (including plans) that were in accordance with Hydraulic Code Rules or design guidelines, 6) the percent of culverts that did not meet the permit specifications for each structural dimension, 7) the mean percent difference or mean simple difference between permitted and actual structural dimension, and 8) the percentage of culverts that were not fish passage barriers.

The logic of the statistical test for trends is as follows (Howell 2015). If there is no trend, i.e., the null hypothesis is true, then the correlation between the data (or an annual statistic) and time is expected to equal 0. The randomization method holds time constant but randomly recombines (shuffles with replacement) the temporal sequence of data. For each random combination, the data's correlation with time is calculated. By repeating this process a large number of times, we build a sampling distribution for *r*. We have only 5 years of data, so we can calculate the correlation, *r*, for every possible combination ($5^5 = 3125$ combinations). Because each data value is randomly paired with a year, the expected value of *r* is 0. We then calculate the actual correlation for the observed data, and determine the proportion of randomized correlations that were greater than the observed *r*.[19] This proportion is the *p* value. If the *p*

[19] If the observed correlation is less than zero, then we determine the proportion of randomized correlations that are less than the observed correlation.

value is less than our threshold for statistical significance, then we conclude that the observed correlation was not due to chance.

We also used randomization methods to test whether the presence of permit provisions for a structural dimension would affect the percentage of culverts that met permit specifications. We applied randomization methods to contingency tables with one fixed marginal (Howell 2009, 2011). The contingency tables were the following form:

		specification		
		met	not met	total of rows
Permit	with provision	*a*	*c*	*a + c*
	without provision	*b*	*d*	*b + d*
	total of columns	*a + b*	*c + d*	

where *a*, *b*, *c*, and *d* are frequencies (i.e., counts). Because we visited almost every new culvert every year, we assumed that the row totals were fixed. Randomization involved simulating with a Monte Carlo method possible pairings of *a* and *c* and of *b* and *d* that equaled the fixed row totals. For each randomized contingency table, the χ^2 statistic was calculated.[20] We determined the proportion of randomized χ^2 that were greater than the observed χ^2. This proportion is the *p* value.

The threshold for statistical significance, known as α, is subjective. A commonly adopted threshold is $p < 0.05$, however, $p < 0.10$ is preferred by some scientists. We report when either of these thresholds were met by a statistical test.

Results

Over the five field seasons we visited 263 culverts (Figure 2.2, Table 2.1) for an average of 53 culverts/year. We visited only 34 culverts in 2017 due to reduced funding. The 263 culverts corresponded to 209 HPA permits because many permits covered two or more culverts. We visited culverts in 18 counties, but 28% of them where in King or Snohomish counties (Table A-1). In most years, the field season ran from August to December, inclusive, but 64% of culverts were visited in September or October (Table A-2). Local governments and private entities were responsible for 41 and 30 percent of the culverts we visited, respectively (Table A-3). The about half (49%) the culverts monitored for implementation were stream simulation design (Table 2.1). From 2013 to 2017, the percentage of culverts that were stream simulation design increased significantly from 37% to 68% ($p < 0.10$).

HPA Permit Quality

Over the 5 years, the design type was known for 79% of 263 culverts. That percentage fluctuated from year to year with minimum of 72% in 2015 and a maximum 97% in 2017 (Figure 2.3). The source of information on culvert design type also varied from year to year, and the design type was specified on the permit for only about half of the culverts (51%). When the design type was not on a permit, often only a single statement of design type was found on one of the various documents associated with the HPA: engineering drawings or other plans, the Joint Aquatic Resource Permits Application (JARPA), a summary form for fish passage design (provided by Bates et al. 2003), a “basis for design” report, other

[20] $\chi^2 = \sum (O_i - E_i)^2 / E_i$, where *O* and *E* are observed and expected frequencies, respectively, and *i* refers to cells in a contingency table.

types of written reports, or a cover letter (Figure 2.3). In 2017, information on design type could be found for 97% of culverts, but only 68% of culverts had design type on their permit.

Table 2.1. Number of culverts monitored each year, and percent of culverts by design type per year. Includes bottomless culverts. Average percent is weighted by number of culverts.

		Year					Average
		2013	**2014**	**2015**	**2016**	**2017**	**Percent**
	total number	54	64	58	53	34	263
Design Type	no slope	39	23	26	21	29	27
	stream simulation †	37	55	47	45	68	49
	hydraulic	0	2	0	4	0	1
	alternate plans	0	2	0	8*	0	2
	unknown	24	19	28	23	3	21

* According to plans, structures were "bridges", but the HPAs described them as culverts. These HPAs also included provisions for stream simulation culverts although "stream simulation" is not explicitly stated in the HPAs.

† Statistically significant trend, $0.05 < p < 0.10$.

An HPA permit should have a specification for every critical structural dimension either on the permit or in the project's plans. Nearly all permits indirectly included specifications for one or more structural dimensions via a provision such as, "APPROVED PLANS: You must accomplish the work per plans and specifications approved by the Washington Department of Fish and Wildlife . . . ." For 2014 through 2017, the combination of permit provisions and project plans resulted in specifications for 89% of critical structural dimensions per year; the minimum of 86% occurred in 2015 (Figure 2.4, Table 2.2). Specifications were most often found for culvert length (97% of permits), followed by culvert slope (93%), minimum countersink at outlet (91%), and maximum countersink at inlet and culvert width at streambed (both 83%) (Table 2.2). Maximum countersink showed the biggest improvement over time. Before July 2015, maximum countersink was not mentioned in the Hydraulic Code Rules, and only 79% of culverts in 2014 and 2015 had specifications for maximum countersink. After maximum countersink became part of the rules, 88% of culverts had specifications for maximum countersink.

Prior to July 2015, provisions stating the permitted specification of each critical structural dimension were left to the discretion of habitat biologists. After that date, provisions for each critical structural dimension were expected to be in every HPA permit, and the HPA permit template for culverts contained standard provisions for each structural dimension (R. Thurston, Protection Division manager, pers. comm.). Seventy-nine percent of culverts monitored in 2016 and 97% of culverts monitored in 2017 were permitted after July 2015. Hence, the vast majority of culverts built in the 2016-2017 time period should have had provisions for every critical structural dimension. This did not happen – for all critical structural dimensions, only 54% had a permit provision in the 2016-2017 period (Table 2.2, Figure 2.5). However, between the 2014-2015 and 2016-2017 time periods, all five critical structural dimensions showed an increase in the percentage of permits that included an explicit provision for it. Three structural dimensions – width, maximum countersink and length –showed substantial increases in the percentage of permits that included a provision. From 2014 to 2017, the biggest improvements for including provisions were for culvert width at streambed (from 47% to 68%) and maximum countersink (from 24% to 49%). For all critical structural dimensions, from 2014 to 2017, the percentage of structural dimensions with permit provisions increased significantly from 42% to 61% ($p < 0.05$). The average number of missing provisions per permit for critical structural dimensions declined significantly from a peak of 3.1 in 2015 to 1.9 in 2017 ($p < 0.10$, Figure 2.5). The percent of permits with no missing provisions increased significantly from 0% in 2014 to 29% in 2017 ($p < 0.05$).

Our examination of permit accordance found that for 2014 through 2017, 88% of provisions were accordant with Hydraulic Code Rules or design guidelines (Table 2.3). Every year at least 85% of provisions for critical structural dimensions were accordant. The accordance rate increased significantly from 85% in 2015 to 95% in 2017 ($p < 0.10$). Accordance with rules or guidelines was highest for culvert slope (100% of provisions), followed by maximum countersink at inlet (94%), minimum countersink at outlet (91%), length (91%), and culvert width at streambed (64%). Culvert width had the lowest rate of accordance over all four years combined, but it also showed the biggest improvement, increasing from 47% of provisions to 86%, however that trend was not statistically significant. Table 2.5 contains examples of non-accordant permits. The most common error in permits was using a no-slope width provision for a stream simulation culvert.

For the years 2014 to 2017, 24% of no-slope culverts per year, on average, were built on sites where the channel width exceeded 10 ft, which is the maximum channel width stated in the Hydraulic Code Rules (Table 2.4).[21] In the worst year, 2016, 45% (5 of 11) no-slope culverts violated the channel width guideline/rule. Channel widths exceeded guidelines/rules by an average of 2.7, 2.3, and 11.1 feet in 2014, 2015, and 2016, respectively. In 2017, no no-slope culverts violated the channel width guideline/rule. On average per year, 31% of no-slope culverts were built on sites where the channel slope exceeded 3%. In 2014, 53% of no-slope culverts were built on sites with channel slopes greater than 3%, but in 2017 only 10% were. There was a significant downward trend ($p < 0.10$) in the percent of no-slope culverts that were built on sites with channel slope greater than 5%; the percentage declined from 33 to 0. Another common error was not following the guidelines for culvert length.[22] This occurred for both no-slope and stream simulation culverts.

[21] On July 1, 2015 the channel width and channel slope guidelines for no-slope culverts in Barnard et al. (2013) became a rule: WAC 220-660-190(6)(b)(i).

[22] On July 1, 2015 the length guideline for no-slope culverts became a rule: WAC 220-660-190(6)(b)(ii).

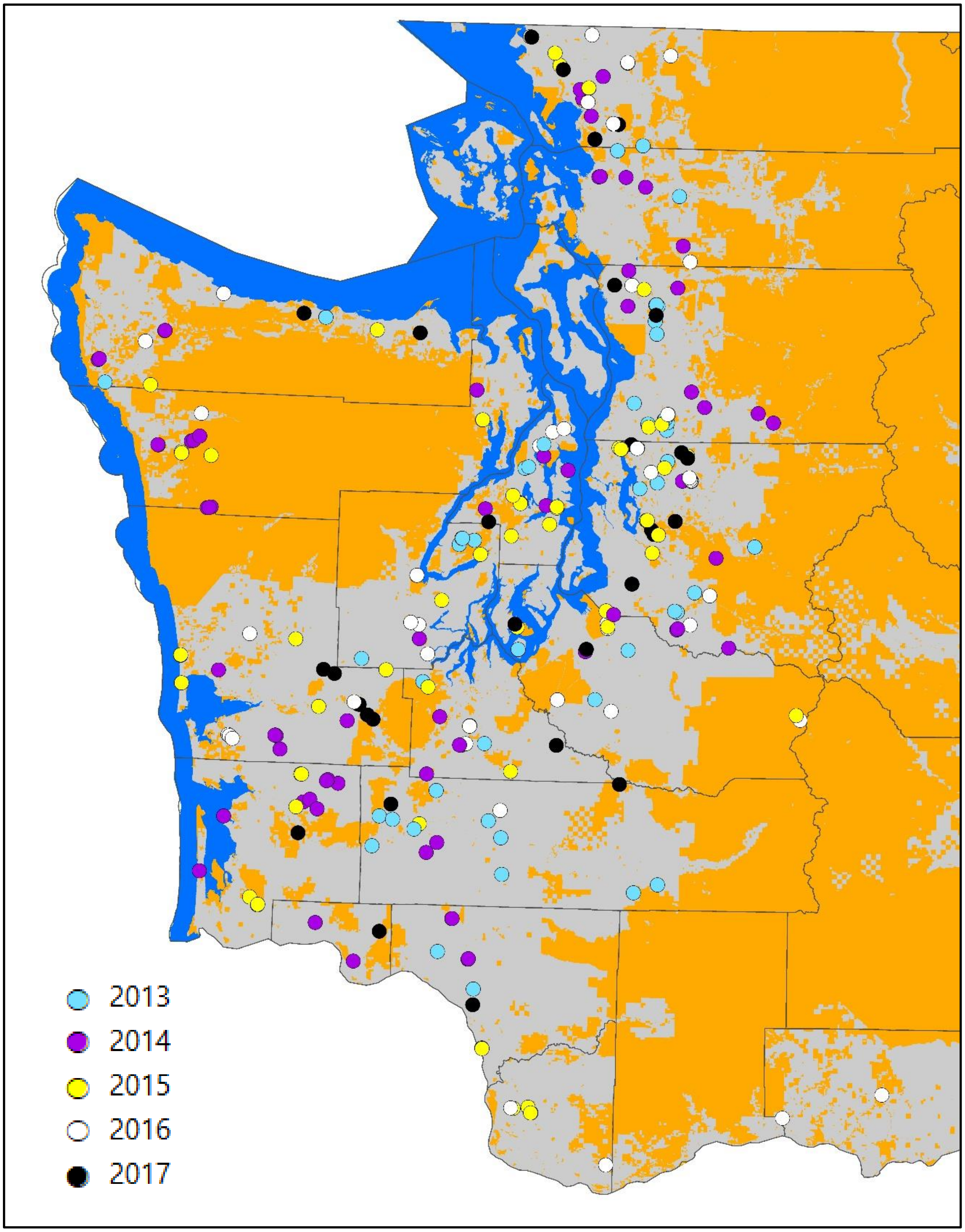

Figure 2.2. Locations of culverts included in implementation monitoring for the years 2013 thru 2017. Orange areas are public lands (federal, state, and county) and tribal lands. Thin black lines are county boundaries.

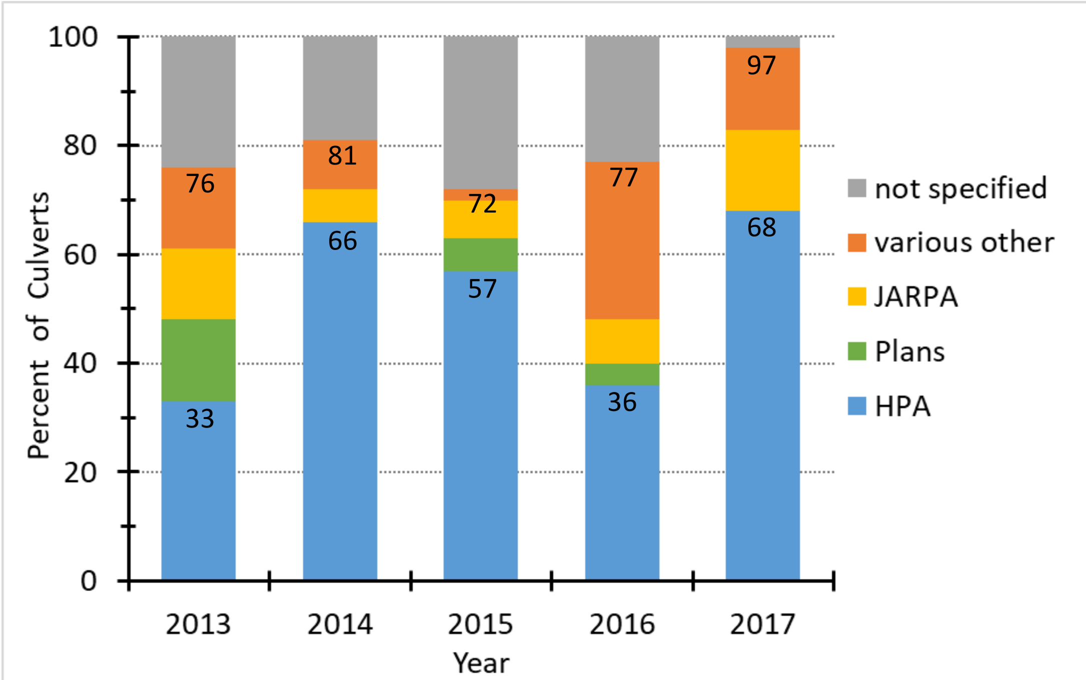

Figure 2.3. Source of information on culvert design type for each year. HPA = Hydraulic Project Approval permit, JARPA = Joint Aquatic Resource Permits Application, and not specified means that the design type could not be found on the permit or any of the supporting documentation. Top number in each column is sum of blue, green, yellow, and orange sections. Bottom number is percentage for HPA permits only.

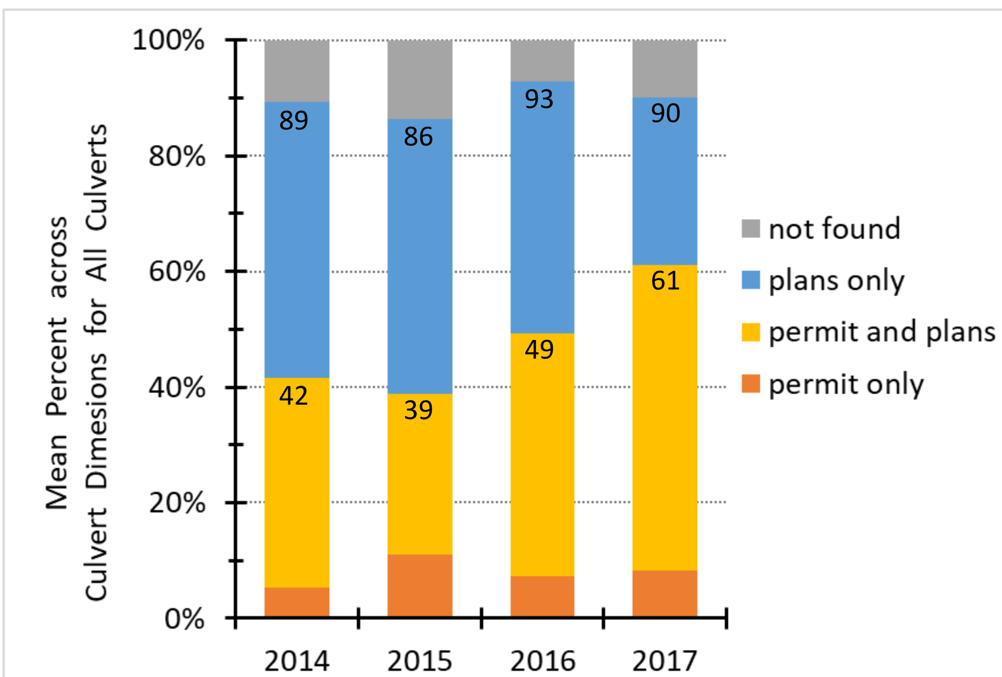

Figure 2.4. Percent of all critical structural dimensions (culvert width at streambed, length, slope, minimum countersink, maximum countersink) for which information could be found on the HPA permit or the project's plans. Top number in each column is sum of blue, yellow, and orange sections. Bottom number is sum of yellow and orange sections.

Table 2.2. Percent of permits with specification of a culvert dimension either on the permit or in the project's plans, and percent of permits with specification of a culvert dimension in a permit provision. A change in HPA permit standards occurred between the 2014-2015 and 2016-2017 time periods.

		Year				**Average Percent**		
Where found	**Culvert Dimension**	**2014**	**2015**	**2016**	**2017**	**All Years**	**2014-2015**	**2016-2017**
Specification in permit or in plans	width at streambed	86	76	87	82	83	81	85
	slope	92	93	96	91	93	92	94
	minimum countersink*	92	90	92	88	91	91	90
	maximum countersink*	83	74	89	88	83	79	89
	length †	94	97	98	100	97	95	99
	all combined	**89**	**86**	**92**	**90**	**89**	**88**	**91**
Specification in a permit provision	width at streambed †	48	45	66	71	55	47	68
	slope	36	28	36	44	35	32	39
	minimum countersink*	52	59	50	65	56	55	56
	maximum countersink* †	23	26	38	65	34	24	49
	length	48	36	58	62	49	42	60
	all combined †	**42**	**39**	**49**	**61**	**46**	**41**	**54**
	total number of culverts	64	58	53	34	209	122	87

* We assumed that minimum countersink provisions generally refer to the culvert outlet and maximum countersink provisions generally refer to the culvert inlet. This is consistent with the Hydraulic Code Rules (WAC 220-660-190(6)).

† Statistically significant trend, $p < 0.05$.

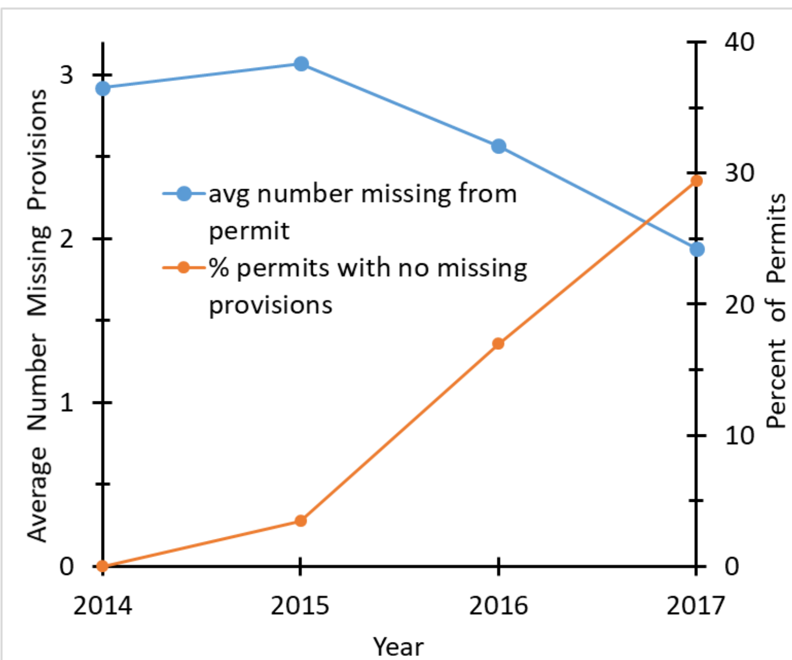

Figure 2.5. Average number per permit of missing provisions for critical structural dimensions, and percent of permits with no missing provisions for critical structural dimensions. Both trends are statistically significant, the former for $p < 0.10$ and the latter for $p < 0.05$.

Table 2.3. Percent of permits with a provision for a culvert dimension *and* that provision was accordant with Hydraulic Code Rules or water crossing design guidelines. Number in parentheses is number of permits that had a provision which could be evaluated for that structural dimension. For example, in 2014, we found provisions for width at streambed on 21 permits and 62% of those provisions were in accordance with Hydraulic Code Rules or water crossing design guidelines.

Culvert Dimension	Year 2014	2015	2016	2017	Average Percent
width at streambed	62 (21)	47 (17)	53 (15)	86 (21)	64 (74)
slope	100 (15)	100 (14)	100 (19)	100 (14)	100 (62)
countersink at outlet*	85 (27)	93 (30)	85 (20)	100 (21)	91 (98)
countersink at inlet*	92 (12)	88 (17)	94 (18)	100 (21)	94 (68)
length**	92 (27)	90 (21)	90 (29)	90 (21)	91 (98)
all combined †	**85** (102)	**85** (99)	**86** (101)	**95** (98)	**88** (400)

* In 2014 and 2015 we looked for provisions for minimum and maximum culvert countersink. We assumed that minimum countersink refers to the outlet and maximum countersink refers to the inlet.

** In 2016 and 2017, accordant length for no-slope culverts must not exceed 75 ft (WAC 220-660-190(6)(b)) and for stream simulation culverts the length/span ratio must be not exceed 10 (Bernard et al. 2013).

† Statistically significant trend, $0.05 < p < 0.10$.

Table 2.4. Statistics for no-slope culverts that did not conform to design guidelines (years 2014, 2015) or Hydraulic Code Rules (years 2016, 2017) for channel width or channel slope. Culverts with channel slopes greater than guideline/rule had channel slope too large either upstream or downstream of culvert. Channel width and slope estimates done by implementation monitoring field crew.

Culvert Dimension	Year 2014	2015	2016	2017	Average
total number of no-slope culverts	15	15	11	10	--
channel width > 10 ft (% of culverts)	20	27	45	0	24
mean channel width of channels > 10 ft (ft)	12.7	12.3	21.1	0	11.9
channel slope > 3% (% of culverts)	53	20	36	10	31
channel slope > 5% † (% of culverts)	33	13	18	0	17

† Statistically significant trend, $0.05 < p < 0.10$.

Overleaf: **Table 2.5**. Examples of HPA permit provisions or project plans that did not accord with WDFW's Water Crossing Design Guidelines (Barnard et al. 2013) or Hydraulic Code Rules (WAC 220-660-190).

Year	Example	Explanation
2015	Permit said, "Culvert width at streambed shall be equal to or greater than the average width at streambed."	This was a no-slope provision for a stream simulation culvert design.
	"Width between the culvert footings for a bottomless culvert shall be equal to or greater than the average width of the streambed."	This was a no-slope provision for a stream simulation culvert design.
	Countersinking provisions state a minimum of 50% countersunk.	50% is the maximum countersink for stream simulation culverts.
	Stream simulation culvert countersunk > 50% in plans.	50% is the maximum countersink according to the guidelines. This occurred at least 3 times in 2015.
	No-slope culvert countersunk to 43 – 47%	40% is the maximum countersink for no-slope culverts
	No bed material shown in plans or specified in HPA permit	
	"Countersink the stream simulation culvert a minimum of thirty percent and maximum of fifty percent of the culvert, but not less than 2 feet."	This was a small no-slope culvert. 2 ft was over 40% of the culvert rise, which is the maximum for no-slope culverts.
	No-slope culvert. HPA states that the culvert must not exceed 80 ft	No-slope culverts should not exceed 75 ft, which is in the guidelines and new rules.
	culvert length = 100 ft, culvert span = 9 ft, length/span = 11	Design type unknown. If it was no-slope, then it should be less than 75 ft long. If it was stream simulation, then length-to-span ratio should be less than 10.
	Length-to-span ratio = 100 ft / 5 ft = 20	stream simulation culvert, so length-to-span ratio should be less than 10.
	upstream channel slope = 2.5%; permitted culvert slope = 3.71% 3.7% / 2.5% > 1.25	according to guidelines for stream simulation culvert, the ratio of channel slope to culvert slope should be less than 1.25
2016	Permit said, "The culvert width at the streambed shall be equal to or greater than the average width of the streambed."	This was a no-slope provision for a stream simulation culvert design. Occurred at least 5 times in 2016.
	No-slope culvert length ≥ 80 ft	Maximum length of no-slope is 75 ft. This occurred at least 3 times in 2016.
	Average bed slope outside of the culvert is 3.8%.	Channel too steep for no-slope design.
	countersunk < 30%	Not in accordance with a stream sim. design. Occurred at least 3 times in 2016.
	countersunk > 50%	Not in accordance with a stream sim. design.
	Upstream slope according to the plans is 1.8%. Permitted culvert slope is 2.7%. 2.7% / 1.8% > 1.25	according to guidelines for stream simulation culvert, the ratio of channel slope to culvert slope should be less than 1.25
2017	Permit said, "Culvert width at the streambed shall be equal to or greater than the average width of the streambed."	This was a no-slope provision for a stream simulation culvert design. This occurred at least 2 times in 2017.
	Culvert was stream sim. design. Based upon BFW in supporting documentation, culvert width at streambed was not 1.2 • BFW+ 2 ft.	Does not meet stream simulation design criteria.
	length = 90 ft, span = 7 ft, therefore length/span = 13	stream simulation culvert, so length-to-span ratio should be less than 10.
	length = 150 ft, span = 12.5 ft, therefore length/span = 12	stream simulation culvert, so length-to-span ratio should be less than 10.
	countersunk < 30%	Not in accordance with a stream sim. design. Occurred at least 2 times in 2017.
	countersunk > 50%	Not in accordance with a stream sim. design. Occurred at least 2 times in 2017.
	backfill of culvert with bed material for countersinking not required	Assumes culvert will fill to correct countersink depth through natural sediment transport and deposition.

Channel Width Estimates

Channel width estimates by permittees tended to be narrower than our estimates of bankfull width. On average, over the 5 years, 59% of estimates per year were narrower (Figure 2.6); the other 41% were wider than our estimates obtained through implementation monitoring. This rate changed over time. In 2013, 81% of permittees' estimates were narrower than ours, but in 2017, 62% were narrower. When permittees' channel width estimates were narrower, they were on average, over the 5 years, 28% narrower than our channel width estimate. This rate stayed roughly constant over the 5 years of monitoring.

There were large discrepancies between permittees' channel width estimates and our estimates of bankfull width (Figure 2.7). From 2013 to 2017, only 24% of channel width estimates done by permittees were within ±10% of our estimates of bankfull width, and this value changed little over time. The percentage of permittees' estimates that were within ±10% our estimates fluctuated between 22% and 27% over five years. Fourteen percent of estimates done by permittees were not even within ±50% of our estimates.

One explanation for the large discrepancy between our bankfull width estimates and those of permittees is that we are measuring different channel features. Over the 5 years of monitoring, permittees used at least 16 different terms to describe channel width (Table 2.6). Some terms used by permittees, such as "bankfull width" and "ordinary high water," are well-defined. Other terms, such as "channel width" or "streambed width", have no widely accepted meaning. The number of terms used by permittees declined significantly over the 5 years from 11 to 4 per year ($p < 0.05$).

Our ability to evaluate permittees' estimates of bankfull width was contingent on finding their estimates. For all years combined, we could find channel width estimates for 59% of permits (Table 2.6). However, this percentage had an increasing trend (albeit not statistically significant) from 47% in 2015 to 79% in 2017. Channel width estimates from permittees were found in application materials, project plans, or various reports submitted by the permittee. Over the 5 years of monitoring, channel width estimates were found in 9 different types of documents per year, on average.

Effects of Provisions

We examined whether the presence of permit provisions for structural dimensions affected permittees' construction of culverts. That is, we wanted to know whether culverts with a specific provision for a structural dimension were more likely to meet a permit's specification than culverts without specific provisions. Overall, we found that the presence of a permit provision did not affect the percent of culverts that met the permit specification for a structural dimension. For example, over the four years, 41% of culverts with a width provision were too narrow and 48% of culverts without a width provision were too narrow (Table 2.7). Furthermore, in two years a higher percentage of culverts without a width provision were too narrow, but in two other years, a higher percentage of culverts with a width provision were too narrow. Culverts with and without provisions for width both exhibited similar declining trends in the percentage of culverts that were too narrow (Figure 2.9), and both trends were significant for $p < 0.10$. For culvert slope, only one year (2016) out of four showed a significant affect ($p < 0.5$) of permit provisions on culvert slope. In that year, no culverts with a provision for slope had an actual slope that was outside the ±1% engineering tolerance for slope, but 21% of culverts without a provision for slope were outside the 1% tolerance. For the three years that countersink was measured with the engineer's method, the χ^2 contingency table test indicated an effect (at least statistically, $p < 0.05$) of permit provisions on culvert countersink. However, the effect was opposite of the expected effect. Seventy percent of culverts with a provision were countersunk too shallow but only 46% of culverts without a provision were too shallow.

The presence of a provision had little effect on the difference between the specification on the permit or plans and the actual culvert dimension. Over four years, the percent difference between permitted and actual culvert width at the streambed was -5.1% for culverts with a width provision and -5.6% for culverts without a provision (Table 2.7, Figure 2.8). For culvert slope, in two years (2015, 2016) culverts without a provision for slope had a bigger difference between permitted and actual slope, but in two other years (2014, 2017) culverts with a provision for slope had a bigger difference between permitted and actual slope. For culvert countersink, in one year (2015) culverts without a provision for countersink had a bigger difference between permitted and actual countersink, but in two other years (2015, 2017) culverts with a provision for countersink had a bigger difference between permitted and actual slope. For the three years that countersink was measured with the engineer's method, the average difference between permitted and actual countersink was larger for culverts with a countersink provision in the permit (-9.8 versus -9.1)

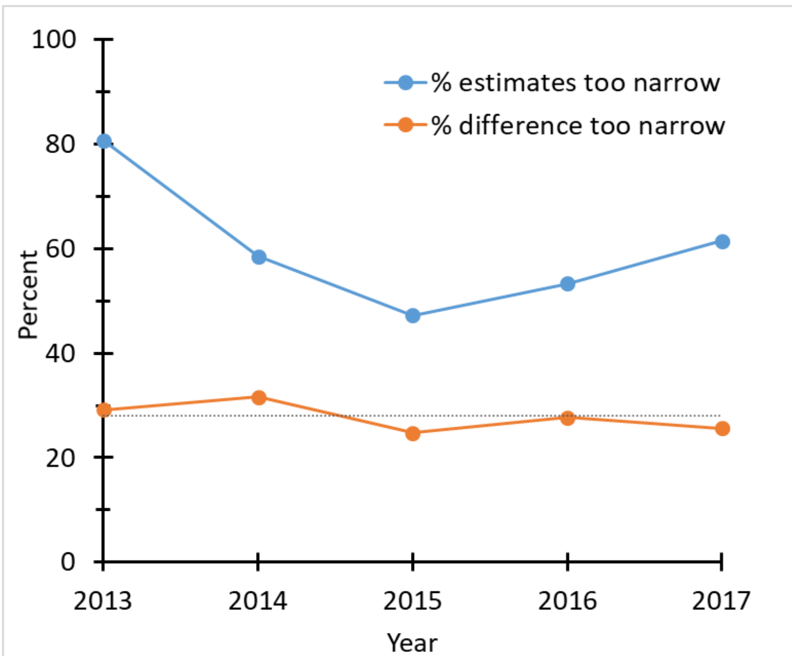

Figure 2.6. Percent of culverts that had channel width estimates by permittee that were narrower than WDFW's bankfull width estimate, and the average percent difference between the two estimates. Percent difference calculated only for those channel width estimates that were narrower than WDFW's estimate. WDFW estimates done by implementation monitoring field crew. Dotted line shows the weighted average of the 5 years (28% narrower).

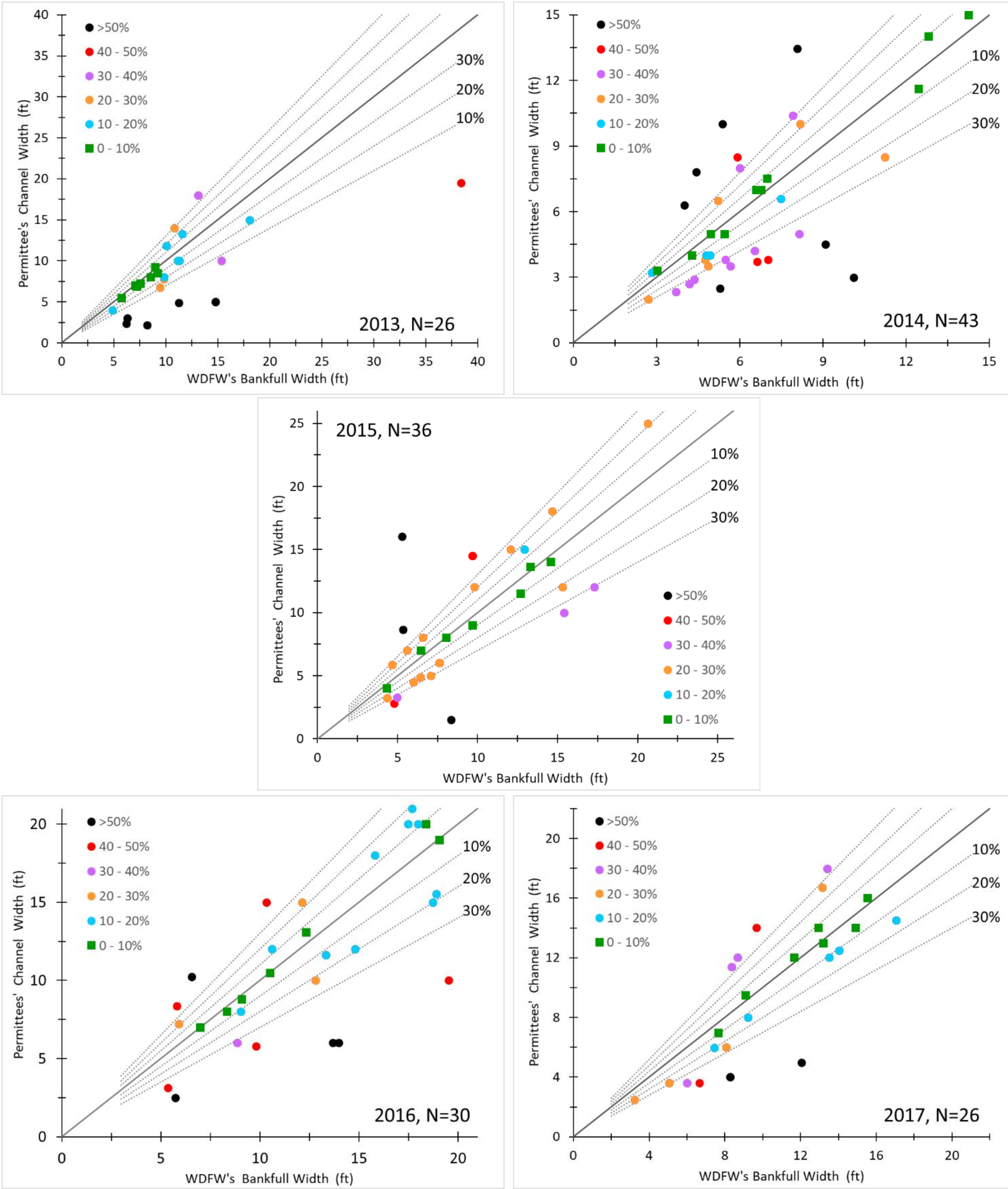

Figure 2.7. Comparison of channel width estimates of permittees with bankfull width estimates of WDFW (i.e., field technicians for implementation monitoring). Square, green markers signify that the permittee's estimate was within ±10% of WDFW's. Permittee's is less than WDFW's when below the solid, 45° diagonal line. Dotted lines and marker colors represent levels of difference between the two estimates. N is the number of culverts that had an estimate for channel width somewhere in HPA application materials, project reports, or project plans.

Table 2.6. Channel width information contained in HPA permit or application materials.

	2013	2014	2015	2016	2017
total culverts	54	64	58	53	34
Percent with channel width estimate	48	67	47	60	79
Terms used to describe channel bed width	Avg. BFW BFW BFW (rough estimate) 2 Year BFW Channel Bed Width Avg. Streambed Width Streambed Width Stream Width Range Stream Width Top Channel Width OHW Mark	BFW Channel Bed Width Channel Width Avg. Streambed Width Design Channel Width Existing Stream Channel OHW	Avg. BFW BFW Avg. Channel Bed Width Channel Bed Width Avg. Channel Width Avg. Width of Stream Bed OHW Mark OHW Channel	BFW Channel Bed Width Channel Width Width at Toe Top Width OHW	BFW Channel Bed Width Channel Width Estimate OHW
Number of different terms †	11	7	8	6	4
First document where channel width estimate was found	HPA FPA Plans/Drawings JARPA Drawing Revisions Summary Form for Fish Passage Design Design Report Critical Areas Study	HPA FPA Plans/Drawings JARPA Application Cover Letter email in HPMS Site visit notes in HPMS FPA Informal Conference Note Hydraulic Analysis Report Fish Passage Design Form Habitat Enhancement Letter Measured from plans	HPA Plans/Drawings JARPA Culvert Design Data Application Form Culvert Design Attachment Habitat Enhancement Letter Site visit notes in HPMS Wetland and Stream Delineation Report Measured from plans	Plans/Drawings Memos Reports Preliminary Basis of Design Memo Addendum to Preliminary Basis of Design Memo Supplement to Preliminary Basis of Design Memo Fish Passage Design Form Design and Data Form RCC Response to WDFW	HPA Plans/Drawings JARPA Preliminary Basis of Design Memo Hydraulic Project Review Fish Passage Design Form Biologist's Notes
Number different documents where first found	8	12	10	9	7

Abbreviations: avg. = average; US = upstream; DS = downstream; BFW = bankfull width OHWM = ordinary high water; HPA = hydraulic project approval, FPA = forest practices application; JARPA = Joint Aquatic Resource Permit Application; HPMS = Hydraulic Permit Management System.
† Statistically significant trend, $p < 0.05$

Table 2.7. Statistics describing whether presence of an explicit permit provision for a critical structural dimension affected permittees construction of culverts, i.e., did the actual dimension meet the permit's specification for that dimension. For culvert width, difference is a percent difference. For slope and countersink, difference is in units of percent (e.g., % slope). For slope, difference between actual slope and slope specified in permit or plans was calculated only for culverts outside a ±1% tolerance.

Statistic	Culvert Dimension	Provision	Year				Average	N
			2014	2015	2016	2017		
Mean difference between actual dimension and permit specification	width at streambed	with	-5	-5.3	-4.5	-6	-5.1	35
		without	-5.8	-4.3	-6.7	-6.7	-5.6	27
	% slope	with	2.53	1.16	0	2.4	1.5	11
		without	2.06	2.2	2.7	1.3	2.2	22
	% minimum countersink	with	NA	-10.3	-7.2	-12.3	-9.8	39
		without	NA	-9.1	-9.1	-9	-9.1	19
Percent of culverts that do not meet permit specification	width at streambed	with *	63	53	16	31	41	35
		without *	75	35	18	25	48	27
	slope	with	26	21	0 †	14	16	11
		without	15	17	21 †	11	17	22
	minimum countersink	with	NA	67 ǂ	74	69	70 †	39
		without	NA	39 ǂ	58	25	46 †	19

* Statistically significant trend, $0.05 < p < 0.10$.
ǂ Statistically significant effect in contingency table, $0.05 < p < 0.10$
† Statistically significant effect in contingency table, $p < 0.05$

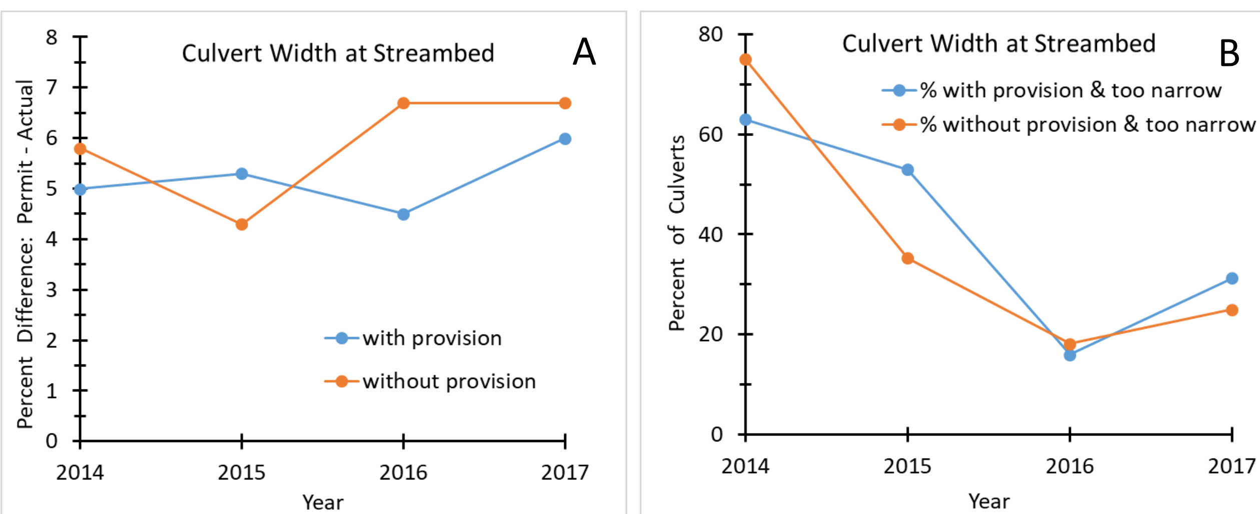

Figure 2.8. Relationships between presence of an explicit provision for culvert width on an HPA permit and (A) the percent difference between the actual and permitted width; (B) the percentage of culverts with widths that were too narrow

Quality of Hydraulic Structure Construction

Because we lack clear guidance on the meaning of HPA permit compliance we cannot always determine whether a culvert complies with its permit. We can, however, compare the specifications for each critical structural dimension on the HPA permit (or the project's plans) with the actual structural dimension measured post-construction. We have two ways of making comparisons: 1) determining what percentage of culverts did not meet the specifications on the permit, and 2) for those culverts that failed to meet the permit's specifications, calculating the difference between the specification on the permit and the actual culvert dimension.

For the years 2015 to 2017, 40% of culverts per year (on average) met the permit's specifications for minimum countersink at the culvert outlet.[23] Compared to the other critical structural dimensions, over the same period of time, this was the smallest mean percentage of culverts per year that met specifications on a permit (Table 2.8). For the other structural dimensions, over the same time period, the mean percentage of culverts per year that met their specification on the permit were 70%, 48%, 84%, and 69% for culvert width at bed, culvert length, culvert slope, and maximum countersink at inlet, respectively. Over a longer period of time, 2013 to 2017, the same statistics were 60%, 47%, and 82% for culvert width at bed, culvert length, and culvert slope, respectively (Table 2.8). The average rate at which culverts met permit specifications for minimum countersink at the outlet (40%) was less than 2/3 the rate for maximum countersink at the inlet (69%). However, such a comparison is misleading because by definition maximum countersink can be satisfied by culverts with little sediment at the invert.

Culvert width and culvert slope exhibited positive trends in the mean percentage of culverts per year that met permit specifications (Figure 2.9), however, the trend was statistically significant for only culvert slope ($p < 0.10$). The mean percentage of culverts per year that met permit specifications for length stayed roughly constant with a mean of 47% over the years 2013 to 2017. The mean percentage of culverts per year that met permit specifications for minimum countersink fluctuated between 45% and 34% over the years 2015 to 2017 with a mean of 40% over that time period. Countersink was measured differently in 2013 and 2014, and therefore, the results for those years are not comparable. However, it is interesting to note that the method used in 2013 should bias the results high, the method used in 2014 should bias the results low, and that is exactly what happened (Figure 2.9). For maximum countersink at the inlet, the percent of culverts that met permit specifications averaged 69% for the years 2015 to 2017, and exhibited a flat trend, fluctuating between 70% and 67% over that same time period. Countersink at the inlet was not measured in 2013 and 2014.

For culverts that failed to meet the permit's specifications, the percent difference between the specification on the permit and the actual culvert dimension averaged -7.1% for culvert width at the streambed and 3.7% for culvert length over the years 2013 to 2017 (Table 2.8). Percent difference between the specification on the permit and the actual culvert dimension for width and length both peaked in 2014 and neither exhibited a trend over time (Figure 2.9). For culverts that failed to meet a permit's specification for slope, the mean difference between the specification on the permit and the actual slope was 2.2% over the years 2013 to 2017, and the mean difference exhibited a significant decreasing trend ($p < 0.05$) from 2.8% to 1.9% over that same time period. The percentage of culverts that did not meet the permit specification for culvert slope declined from 23% to 13%, which was a statistically significant trend. For culvert minimum countersink at the outlet, the mean difference between the specification on the permit and the actual countersink was -9.4% over the years 2015 to 2017, and the results from year to year were roughly the same. It is interesting to note that even though outlet countersink was measured differently in 2013 and 2014, the results obtained for mean difference between the specification on the permit and the actual countersink were about the same as those obtained in 2015 thru 2017 using the

[23] Recall that in 2013 and 2014, culvert countersink measured differently than in subsequent years.

correct method. For culverts that failed to meet the permit's specifications for maximum countersink at the inlet, the mean difference between the specification on the permit and the actual countersink was 7.9% over the years 2015 to 2017, and there was no trend over this time period.

Perhaps the best way to understand how well permittees follow their permits when building culverts is to graph the actual culvert dimensions versus specifications on HPA permits for every culvert. Figure 2.10 presents such graphs for culvert width at streambed for the years 2013 to 2017. In these graphs, actual dimensions equal the permit specifications along a 45° diagonal line. For culvert width, points on or above the 45° line meet the permit specification. For all years combined, 60% of culverts met the permit specification for culvert width at the streambed. Points below the 45° line do not meet permit specifications for culvert width at the streambed, however, in every year most points below the line are within 10% of the permit specification. In fact, for all years combined, 80% of culverts that do not meet the permit specification for culvert width at the streambed are within 10% of the specification.

A point's distance from the 45° line represents the accuracy of culvert construction. The large proportion of markers (green dots) on or very close to the 45° line illustrates the accuracy with which permittees can build culvert width to permit specifications. For all years combined, culvert width at the streambed was built within ±10% of the permit specification for 84% of culverts. The graphs indicate no relationship between culvert width and construction accuracy (Figure 2.10). That is, accuracy does not appear to change as culvert width increases.

For culvert length, points on or below the 45° line meet the permit specifications (Figure 2.11). For all years combined, 47% of culverts met the permit specification for length. However, again, in every year most points above the line are within 10% of the permit specification. For all years combined, 90% of culverts that do not meet the permit specification for culvert length at the streambed are within 10% of the specification, and 85% are within 5% of the permit specification. For all years combined, culvert length was built within ±10% of the permit specification for 89% of culverts.

Culvert slope is the only critical structural dimension that has a recommended construction tolerance in WDFW's Water Crossing Design Guidelines (Barnard et al. 2013, p. 205). Based on the guidelines, we decided upon a tolerance of ±1% for culvert slope. Hence, for our purposes only, points within ±1% of the 45° line meet the permit specification for slope (Figure 2.12). For all years combined, 82% of culverts met the permit specification for slope. Most no-slope culverts had actual slopes between -1% and 1%. However, the actual slope of no-slope culverts permitted with zero slope ranged from -2% to about 4.5%. There was no consistent bias toward building culverts with slopes that were too steep or too gentle relative to the permit specification (Figure 2.15). For all years combined, 46% of culverts were steeper than the slope specified in the permit and 44% were gentler.

For culvert minimum countersink at the outlet, points on or above the 45° line meet the permit specification (Figure 2.13). For all years, only 40% of culverts met the permit specification for minimum countersink. However, an additional 20% of culverts were within 5% of the specified countersink depth. Each year at least one culvert had zero countersink because the culvert was not backfilled with sediment. Some culverts met the specification for minimum countersink but may have been countersunk too deep. In 2015, for example, several culverts were permitted at 20% minimum countersink but were countersunk between 40 and 50%. For culvert maximum countersink at the inlet, points on or below the 45° line meet the permit specifications (Figure 2.14). Sixty-nine percent of culverts met the permit specification for maximum countersink. An additional 13% of culvert were within 5% of the specified countersink depth.

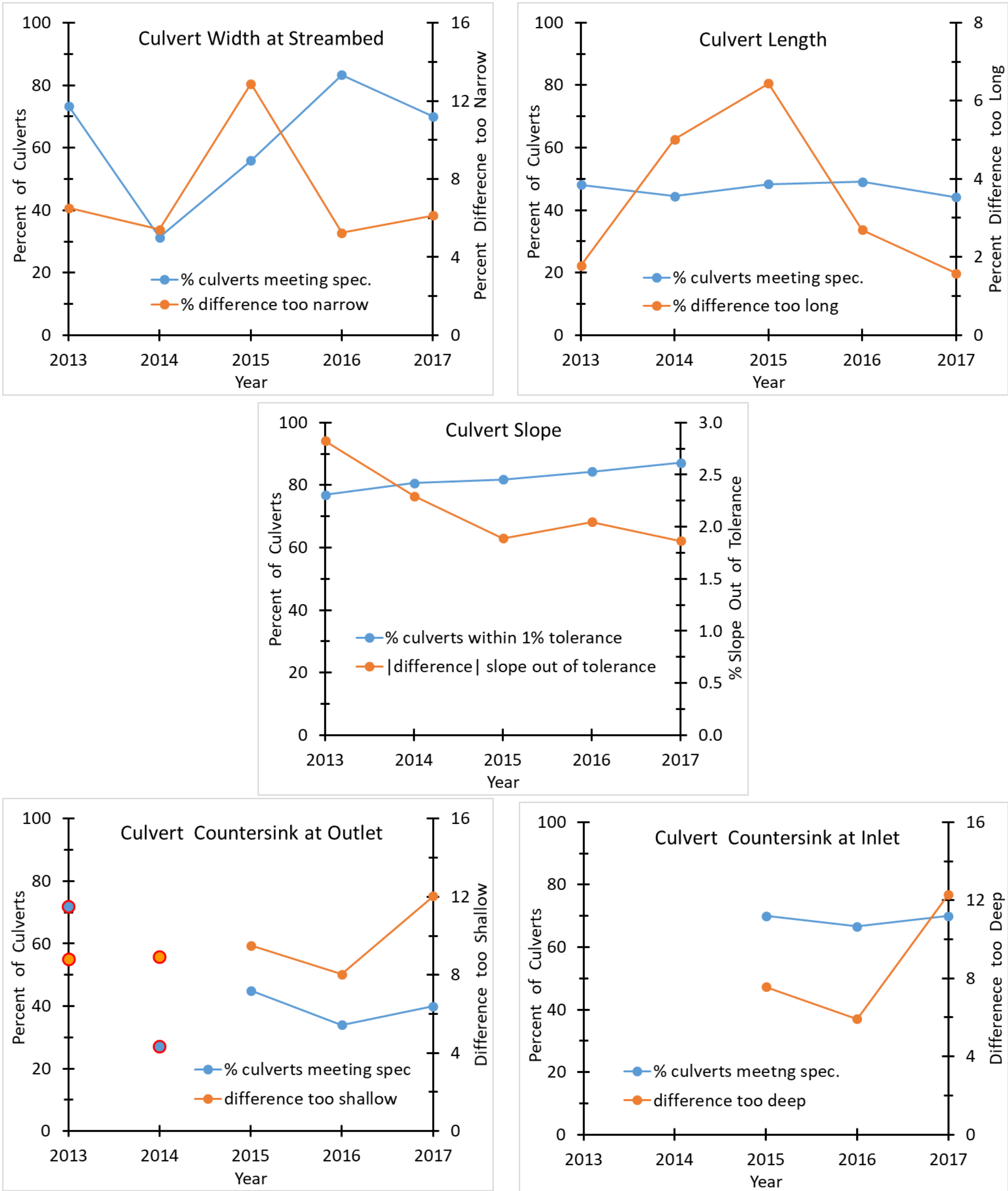

Figure 2.9. Percent of culverts that met specifications in permit or plans for each of the 5 critical culvert dimensions, and the mean difference between the permit's specification and the actual dimension, expressed as either a percent difference (width and length) or a simple difference (slope and countersink). Percent difference between permitted and actual dimensions calculated only for those culverts that did not meet permit (or plan) specifications. That is, it was only calculated for culvert widths that were too narrow, lengths that were too long, etc. Simple difference between permitted and actual slope (in units of percent slope) calculated only when actual culvert slope not within 1% of permitted culvert slope. No tolerances applied to other four structural dimensions. In graph for culvert countersink at outlet, red circles indicate years in which countersink measured differently.

Table 2.8. Percent of culverts that met specifications in permit or plans for each of the 5 critical culvert dimensions, and mean difference, expressed as either a percent difference (width and length) or a simple difference between permitted and actual dimensions (slope and countersink).

Structural Dimension	Statistic	Year 2013	2014	2015	2016	2017	Sum or Average⁑
width at streambed	N♦	45	51	34	36	20	186
	% met specification	73	31	56	83	70	60
	mean % difference too narrow*	-6.5	-5.4	-12.9	-5.2	-6.1	-7.1
length	N	54	63	58	53	34	248
	% met specification	48	44	48	49	44	47
	mean % difference too long*	1.8	5.0	6.4	2.7	1.6	3.7
% slope	N	39	62	55	51	31	238
	% within tolerance †	77	81	82	84	87	82
	mean % slope difference** †	2.8	2.3	1.9	2.0	1.9	2.2
% minimum countersink at outlet	N	39	52	40	38	20	189
	% met specification	72 ♯	27 ♯	45	34	40	40
	mean % countersink difference‡	8.8 ♯	8.9 ♯	-9.5	-8.0	-12.0	-9.4
% maximum countersink at inlet	N	NA◊	NA◊	40	36	20	96
	% met specification			70	67	70	69
	mean % countersink difference‡			7.6	5.9	12.3	7.9

♦ N is the number of culverts that had a specification for that critical structural dimension on its permit or in the project plans.

† Statistically significant trend, $p < 0.05$.

* Percent difference between permitted and actual dimensions calculated only for those culverts that did not meet permit (or plan) specifications. That is, it was only calculated for culvert widths that were too narrow or lengths that were too long.

** Absolute difference between permitted and actual slope (in units of percent slope) calculated only when actual culvert slope not within 1% of permitted culvert slope. One percent tolerance for slope recommended by Barnard et al. (2013).

‡ Difference between permitted and actual countersink (in units of percent countersink) calculated only for those culverts that did not meet permit (or plan) specifications. That is, it was only calculated for minimum countersink that was too shallow or maximum countersink that was too deep.

⁑ Average weighted by N.

♯ Three different methods for measuring culvert countersink were used in 2013, 2014, and from 2015 to 2017. Culvert countersink at outlet measured differently in years 2013 and 2014. Values for 2013 and 2014 should be considered invalid and were not included in weighted average. See methods section for explanation.

◊ Culvert countersink at inlet not measured in years 2013 and 2014.

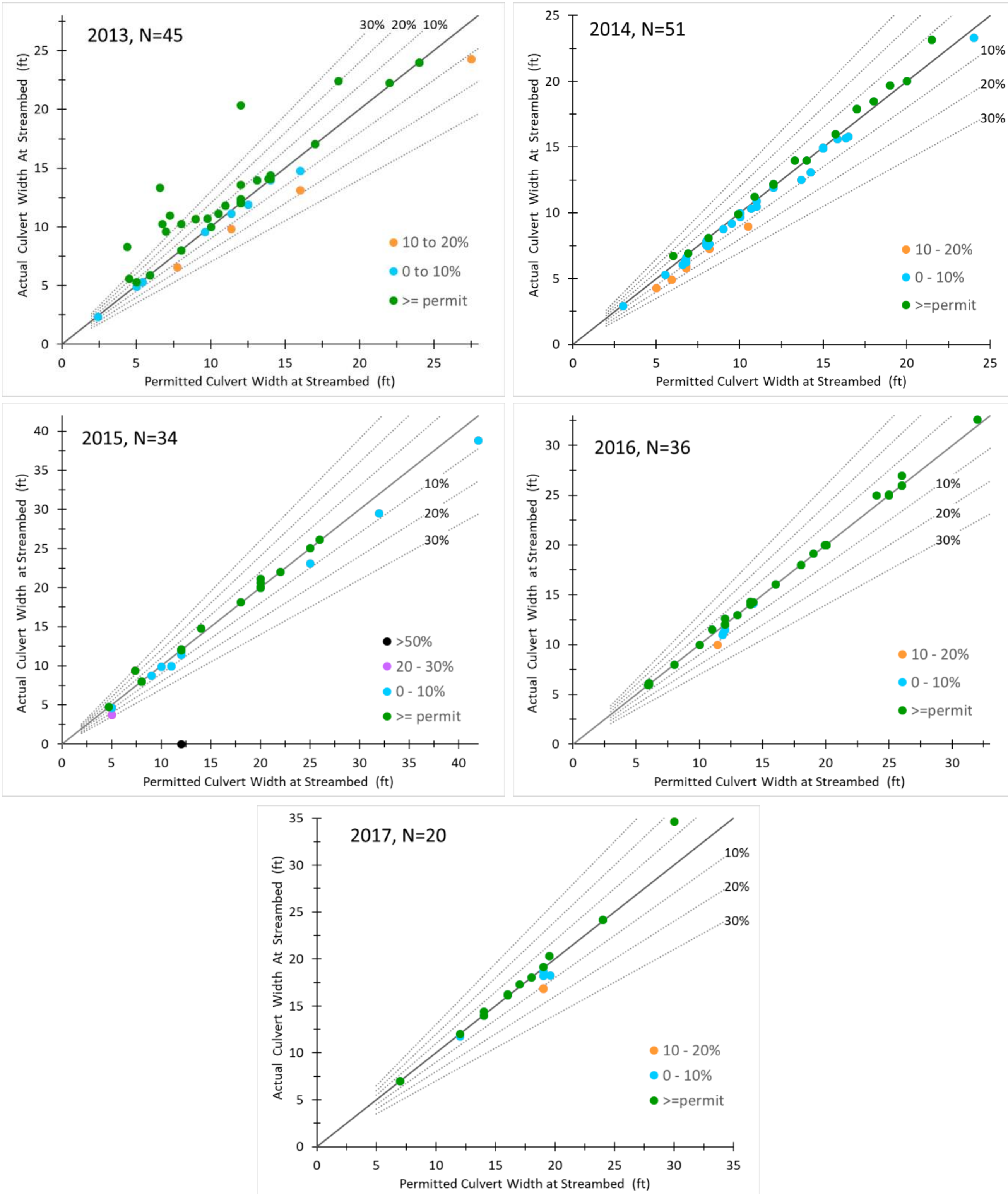

Figure 2.10. Comparison of actual culvert width at streambed with permitted culvert width at streambed. Green markers (points) signify culverts that met permit specifications. Actual width equals permitted width on solid, 45° diagonal line, and dotted lines represent different levels of percent difference between actual and permitted width. N is the number of culverts that had a specification for culvert width at streambed on its permit or in the project plans.

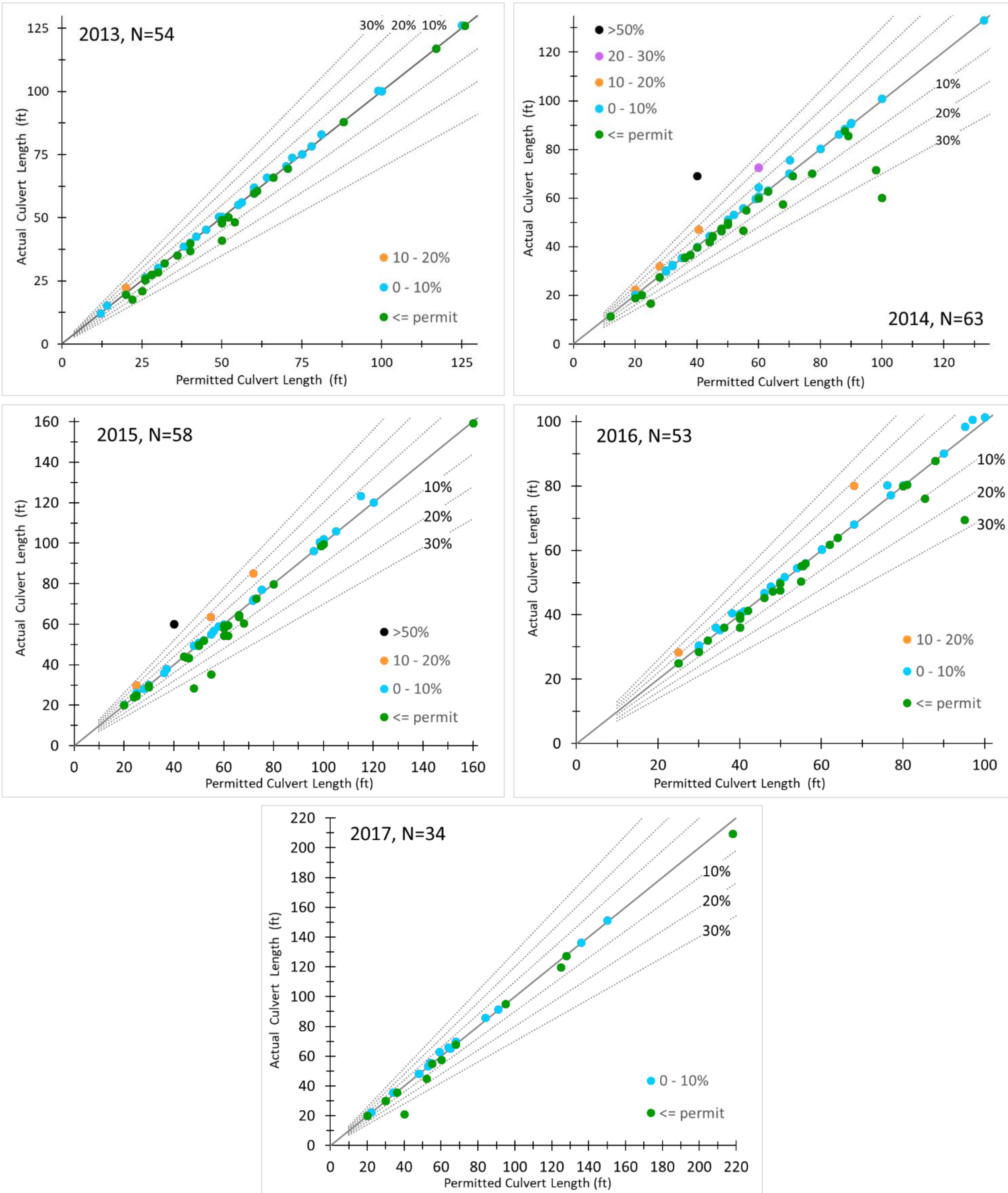

Figure 2.11. Comparison of actual culvert length with permitted culvert length. Green markers (points) signify culverts that met permit specifications. Actual length equals permitted length on solid, 45° diagonal line, and dotted lines represent different levels of percent difference between actual and permitted length. N is the number of culverts that had a specification for culvert length on its permit or in the project plans. Graph for 2014 excludes a point at (299, 300).

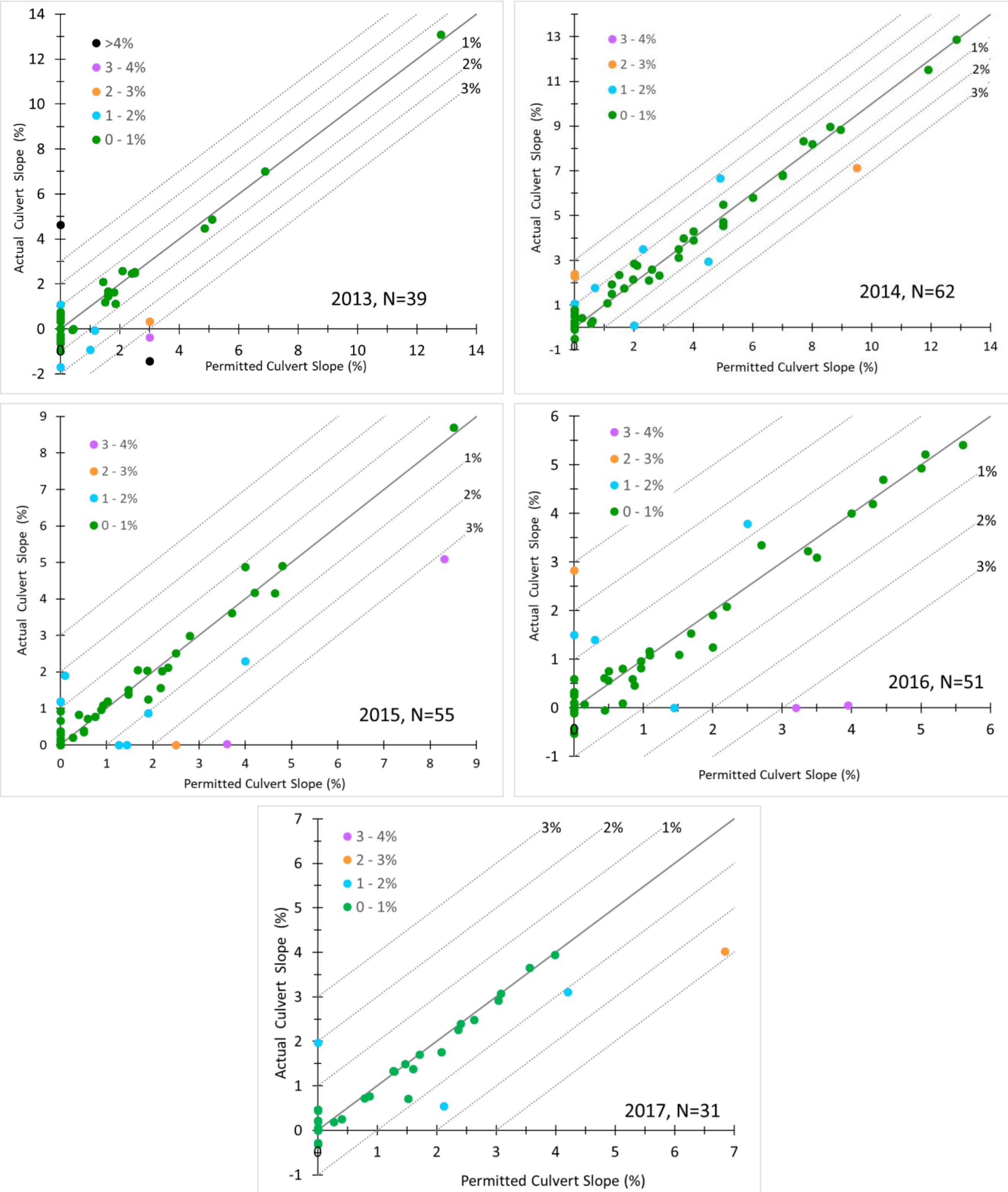

Figure 2.12. Comparison of actual culvert slope with permitted culvert slope. Green markers signify culverts that met permit specifications. Actual slope equals permitted slope on solid, 45° diagonal line, and dotted lines represent different levels of difference between actual and permitted slope. N is the number of culverts that had a specification for culvert slope on its permit or on the project plans.

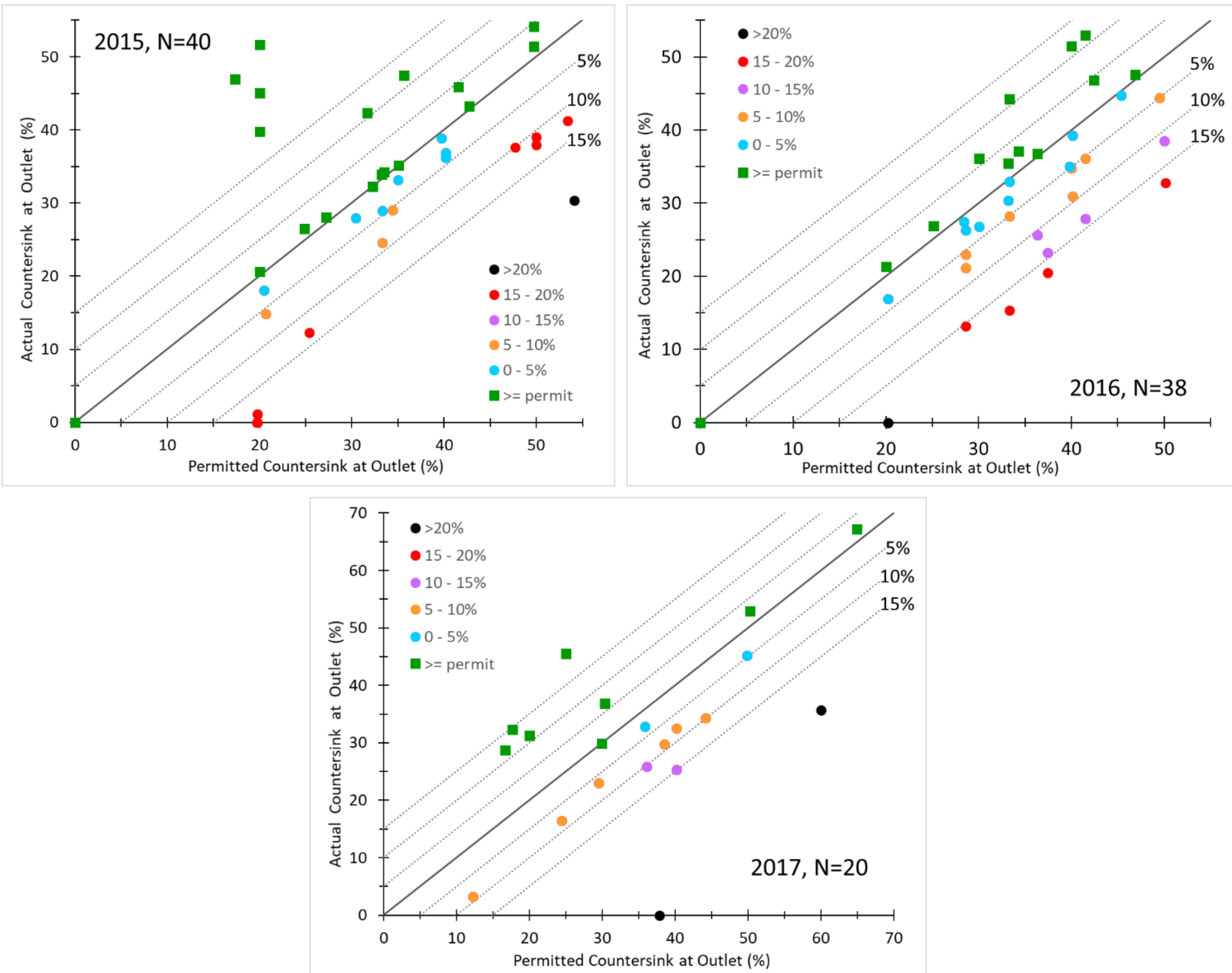

Figure 2.13. Comparison of actual with permitted minimum culvert countersink at the outlet. Square, green markers signify culverts that met permit specifications. Actual countersink equals permitted countersink on solid, 45° diagonal line, and dotted lines represent different levels of difference between actual and permitted countersink. N is the number of culverts that had a specification for culvert minimum countersink on its permit or on the project plans. Culvert countersink at outlet was measured differently in years 2013 and 2014; those results are shown in Figure A-1 of Appendix A.

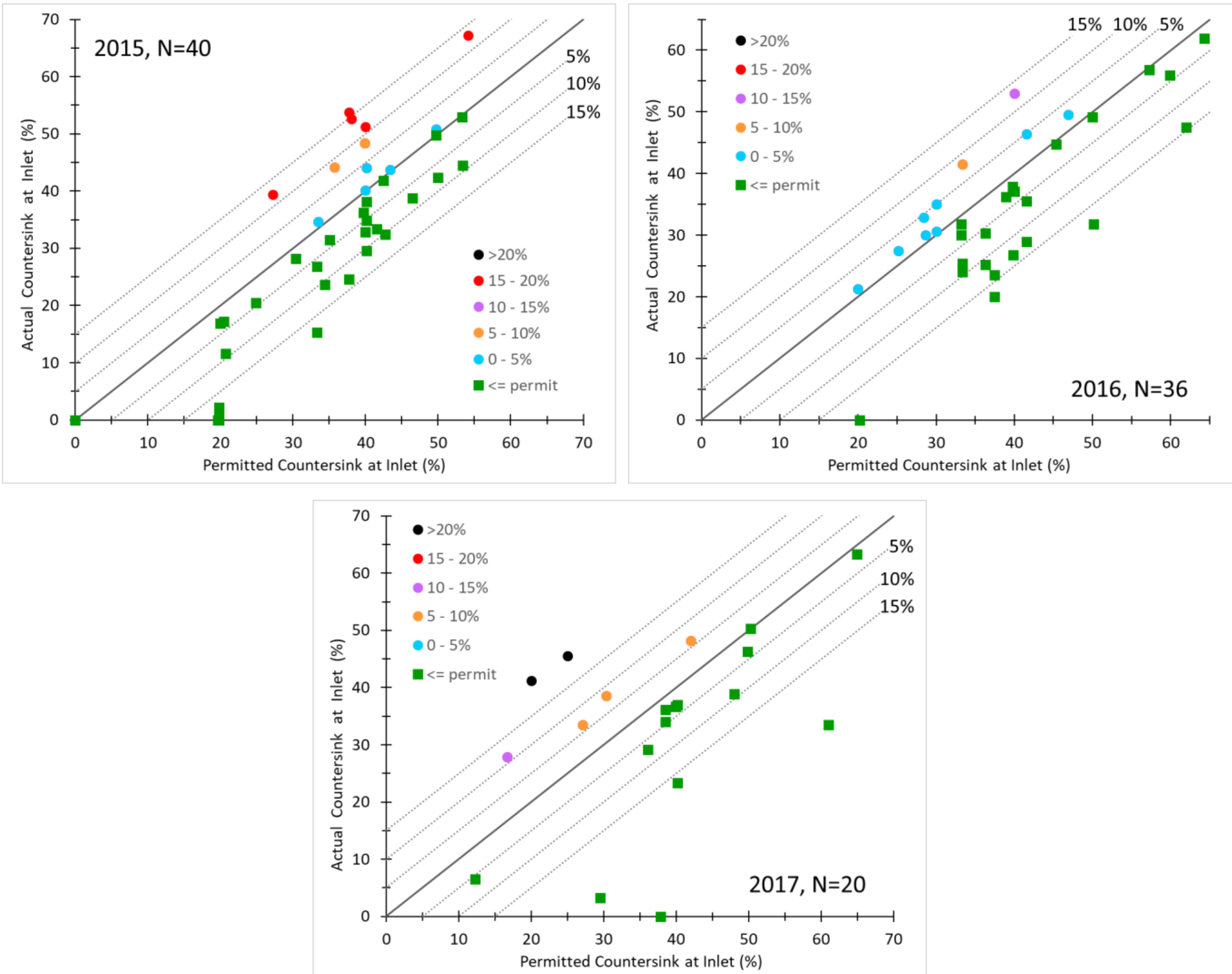

Figure 2.14. Comparison of actual with permitted maximum culvert countersink at the inlet. Square, green markers signify culverts that met permit specifications. Actual countersink equals permitted countersink on solid, 45° diagonal line, and dotted lines represent different levels of difference between actual and permitted countersink. N is the number of culverts that had a specification for culvert maximum countersink on its permit or on the project plans. Culverts that satisfy specification for maximum countersink at inlet may not satisfy specification for minimum countersink at outlet. Culvert countersink at inlet not measured in years 2013 and 2014.

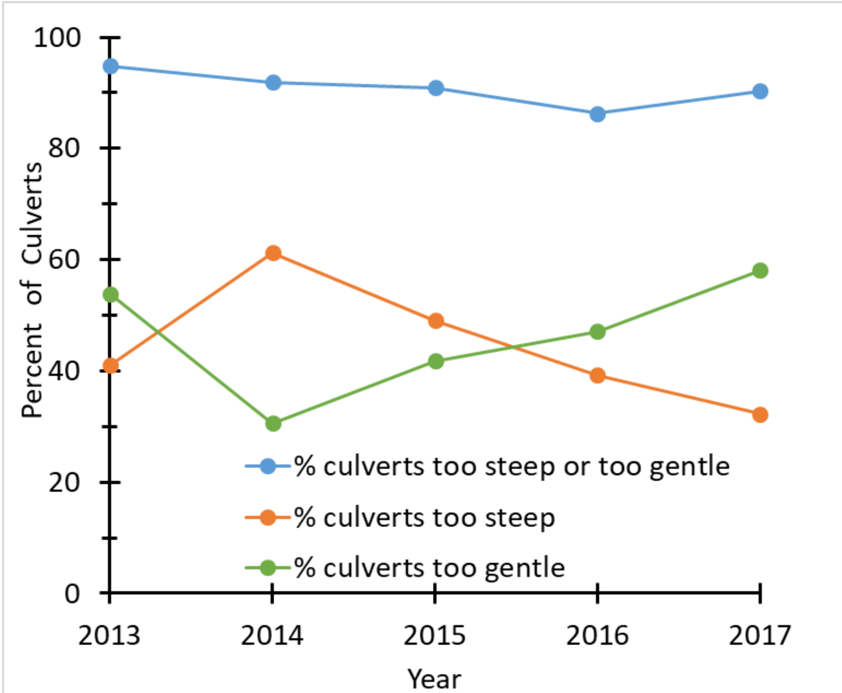

Figure 2.15. Percent of culverts each year constructed with a slope to gentle or too steep.

Fish Passage Barrier Assessment

For the years 2013 through 2016, about 4% of culverts were determined to be fish passage barriers immediately[24] after construction. In 2017, no culverts were found to be barriers. From 2013 to 2017, the percentage culverts that were *not* barriers increased from 89% to 94%, and this trend was statistically significant. Over 5 years of monitoring, 11 culverts were determined to be barriers – 7 failed level A and 4 failed level B. Five of the barriers were complete and 6 were partial (3 were 33% passable and 3 were 67% passable). A more detailed summary of the fish passage barrier assessments is presented in Table A-6.

Table 2.9. Results (percent of culverts each year) of fish passage barrier assessment done for implementation monitoring. Numbers in parentheses indicate number of culverts that were partial fish passage barriers.

	Year					Weighted
Barrier?	**2013**	**2014**	**2015**	**2016**	**2017**	**Average**
% No †	89	87	91	91	94	90
% Yes	2 (1)	8 (1)	6 (3)	4 (1)	0	4
% Unknown	9*	5	3	6	6♯	6
Total Culverts	54	64	58	53	34	263

* No Level B assessments done in 2013. Therefore, the barrier status of culverts that required a Level B assessment is unknown.
♯ One culvert was on a non-fish-bearing stream, and consequently, no barrier assessment was done for it.
† Statistically significant trend, $p < 0.05$

[24] The time between the end of culvert construction and implementation monitoring ranged from about 1 week to 3 months but was typically about 1 month.

Discussion

One goal of WDFW's Habitat Program is for all hydraulic structures to comply with Hydraulic Code Rules and to follow design guidelines (e.g., Barnard et al. 2013, Cramer et al. 2002). To achieve this goal, the Habitat Program initiated implementation monitoring to improve the HPA permitting process and its most important outcome – the quality of hydraulic structures such as culverts. We hope to improve the process by evaluating HPA permits and their consequent hydraulic structures, and then providing feedback (such as this report) to Habitat Program managers.

Results Summary

After five years of implementation monitoring, we have several positive findings about the quality of HPA permits. We found no undesirable trends in permit quality, that is, quality was either fairly constant or improving over time. We report four notable statistically significant trends: 1) the percentage of critical structural dimensions with permit provisions increased from 42% to 61% per year over a period of 5 years; 2) the average number of missing provisions for critical structural dimensions declined from 3.1 per permit (out of 5) to 1.9 per permit; 3) the percent of permits with no missing provisions for critical structural dimensions increased from 0% to 29% per year; and 4) the accordance of permit provisions (including project plans) with guidelines or rules increased from 85% in 2015 to 95% in 2017. The first three trends were effected by a change in standards for HPA permits. Prior to July 2015, provisions stating the permitted specification of each critical structural dimension were left to the discretion of habitat biologists. After that date, provisions for critical structural dimensions were expected to be in every HPA permit. Hence, permits for the vast majority culverts constructed in 2016 and 2017 should have included provisions for every critical structural dimension. This did not happen (see Table 2.2), however, a big change in permit quality occurred between 2015 and 2016 (Figure 2.5), and that trend continued into 2017.

The percentage of all critical structural dimensions with a specification in a permit or plans was at least 90% in 2016 and 2017. In those same years, the percentage of HPA permits with a specification in a permit provision or in the plans averaged at least 89% per year for culvert length, slope, minimum countersink, and maximum countersink, and the average was 85% per year for culvert width. Maximum countersink was not incorporated into the Hydraulic Code Rules until 2015, and after it became a rule, the percentage of permits with a specification for maximum countersink jumped from 79% in 2014-2015 to 89% in 2016-2017 (Table 2.2). Future implementation monitoring will determine whether that positive trend continues.

From 2014 to 2017, the accordance rate for permit provisions for culvert length, minimum countersink, and maximum countersink averaged more than 90% per year, and the accordance rate for culvert slope averaged 100% per year. Accordance rate of culvert width provisions averaged only 64% per year, with the main problem being the use of a standard no-slope provision for stream simulation culverts. However, the accordance rate of culvert width provisions improved from 47% in 2015 to 86% in 2017; that trend was not statistically significant. Again, future implementation monitoring will determine whether that positive trend continues.

While the above results reflect positively on permit quality, there is substantial room for improvement. In particular, many permits were missing important information about culvert design type and critical structural dimensions. Over the years 2013 to 2017, on average, the design type was unknown for 21% of culverts. However, the percentage of unknown types did improve over time: 28%, 23%, and 3% for 2015 through 2017, respectively. Future implementation monitoring will determine whether that trend is maintained. Also, while the annual percentage of critical structural dimensions with explicit permit provisions increased from 42% to 61% per year, 61% is still too low. In 2017, on average, permits were missing about 2 provisions for critical structural dimensions per permit, and 71% of permits were missing a provision for at least one critical structural dimension.

We observed mixed results for no-slope culverts following the design guidelines. Over four years, on average, 24% of no-slope culverts did not conform to design guidelines for maximum channel width. The average was 29% per year from 2014 to 2016, but declined to 0% in 2017. The percentage of no-slope culverts built in stream channels steeper than 5% declined from 33% in 2014 to 0% in 2017, which was a statistically significant trend. The no-slope guidelines for maximum channel width and slope were incorporated into the Hydraulic Code Rules in 2015. The drop to 0% in 2017 for disregarding maximum channel width and channel slope may be because these guidelines became rules, and therefore, were adhered to more strictly. Interestingly, during that same period, the percentage of culverts built as stream simulation design increased from 55% to 68%. Perhaps the increase in stream simulation culverts was due to the new rules for no-slope culverts that established maximum channel width and slope.

From 2013 to 2017, a high percentage of permittees submitted inaccurate channel width estimates. In 2017, for instance, 62% of permittees channel width estimates were, on average, 26% narrower than our (the monitoring field crew's) estimates. In effect, when we measured a 10 ft channel, the permittee measured a 7.4 ft channel. If a permittee's inaccurate channel width estimate were used for culvert design, then the resulting undersized culvert could eventually lead to a fish passage barrier, and a requirement to replace the culvert before the end of its expected service life.

We found that the quality of culvert construction was related to the particular structural dimension. The quality of culvert slope was good. Over the five years of monitoring, 82% of culverts had a slope that was within ±1% of the permit's specification, which is the engineering tolerance recommended by Barnard et al. (2013, p. 204). Bernard et al. (2013, p. 204) also suggested a ±2% "compliance" tolerance for no-slope culverts.[25] If we apply their suggestion to all design types we encountered, and increase the slope tolerance to ±2%, then 93% of culverts met the permit specification for slope (Figure 2.16). Furthermore, from 2013 to 2017, the percent of culverts that met the permit's slope specification (with a ±1% tolerance) steadily increased from 77% to 87%.

The quality of culvert construction for countersink at the outlet was poor. Over three years of monitoring, the percent of culverts that met permit specifications for this structural dimension was only 40%. A 5% compliance tolerance increases that percentage to 60%, and a 10% tolerance increases it to 76%.

The quality of culvert construction for width at the streambed, culvert length, and culvert countersink at the inlet were fair. Over five years of monitoring, the percent of culverts that met permit specifications for width and length were 60% and 47%, respectively. Over three years of monitoring, the percent of culverts that met permit specifications for inlet countersink were 69%. No trends over time were exhibited for any of these three structural dimensions, however, in 2016 and 2017, the percentage of culverts that met the permit's specification for width was well above the 5-year average: 83% and 70%, respectively. We describe the quality of construction as "fair" because when compliance tolerances were incorporated into our analysis, the percentage of culverts that met permit specifications increased substantially (Figure 2.16). Allowing a 5% tolerance increased the percentage of culverts that met permit specifications to 81%, 92%, and 82% for width, length, and inlet countersink, respectively.[26] A 10% tolerance increased those percentages to 92%, 95%, and 89%.

[25] They suggested a ±2% compliance tolerance for no-slope culverts, but we applied it stream simulation culverts too.

[26] Recall that tolerances for culvert width and length were calculated differently than the tolerances for culvert countersink. For width and length, the tolerance was calculated as a percentage of the permit specification. For

Fish Passage Barrier Assessment

Our fish passage barrier assessments found that 4% of 263 new culverts constructed between 2013 and 2017 were barriers. In addition, the percentage of culverts that were not barriers increased from 81% in 2013 to 94% in 2017. While new culverts should never be barriers, this result is a still a substantial improvement over the findings of Price at al. (2010) who found that 25% (5 of 20) 1 to 2-year old culverts were fish passage barriers.

Issues Identified through Implementation Monitoring

We believe that implementation monitoring has identified the following four issues that should be addressed by managers.

First, while staff deserve credit for the improved quality of HPA permits issued for culverts, permit quality can still be much better. Too many permits lacked provisions for at least one of the five critical structural dimensions. This shortcoming may be due to unclear directions to habitat biologists. Prior to July 2015, habitat biologists were not expected to include provisions for each critical culvert dimension. Nevertheless, at that time, many biologists regularly wrote provisions for one or more critical culvert dimensions, especially culvert width at stream bed, and a few biologists wrote provisions for all culvert dimensions. Shortly before July 2015, when training for the revised Hydraulic Code Rules occurred, habitat biologists were asked to include provisions for each critical culvert dimension, and the new HPA permit template included those provisions. However, expectations were apparently unclear. While reviewing this report, two Habitat Program staff from separate regions stated that culvert dimensions in plans should not need to be repeated in permit provisions.

Missing information on HPA permits is an important issue because the permit is the most authoritative record of WDFW's decision with respect to a particular hydraulic structure. The permit should clearly state, for the benefit of the permittee and WDFW staff, specifications for each of the five critical structural dimensions. Nearly all HPA permits reference the project's plans for a culvert's structural dimensions. However, critical structural dimensions are sometimes missing from project plans, or plans use terminology different from that used in the Hydraulic Code Rules. Plans can simply be difficult to read. Surprisingly, our results show that the presence of an explicit provision for a structural dimension had no effect on whether a culvert meets the permitted specification. This result is consistent with the opinion of a habitat biologist who believes that contractors, i.e., firms responsible for culvert construction, rarely refer to the permit. Contractors refer to the project's plans, and not the permit, because their clients' expectations (i.e., the job they are paid to do) are conveyed by the plans. Nevertheless, now that WDFW has civil enforcement authority for HPA permit violations, provisions for each structural dimension may be necessary to avoid any misunderstandings between WDFW and the permittee or between WDFW and the court.

Important information was missing for a substantial proportion of culverts. Over the five years, design type and channel width were missing for 21% and 41% of culverts, respectively. Furthermore, specifications were missing from permits and plans for 11% of critical structural dimensions. However, we are unsure whether this information was absent or we simply could not find it. Some information was difficult to locate amongst the many pages of plans, the JARPA, reports, and other supporting documentation. Original engineering drawings are either 11 inches x 17 inches or 22 inches x 34 inches, but the drawings attached to HPA permits are usually 8.5 inches x 11 inches – a 50% or 87% reduction in size, respectively. This size reduction plus the loss of fidelity after scanning and printing make the

maximum inlet countersink, the percent tolerance was added to the permit specification. For minimum outlet countersink, the percent tolerance was subtracted from the permit specification.

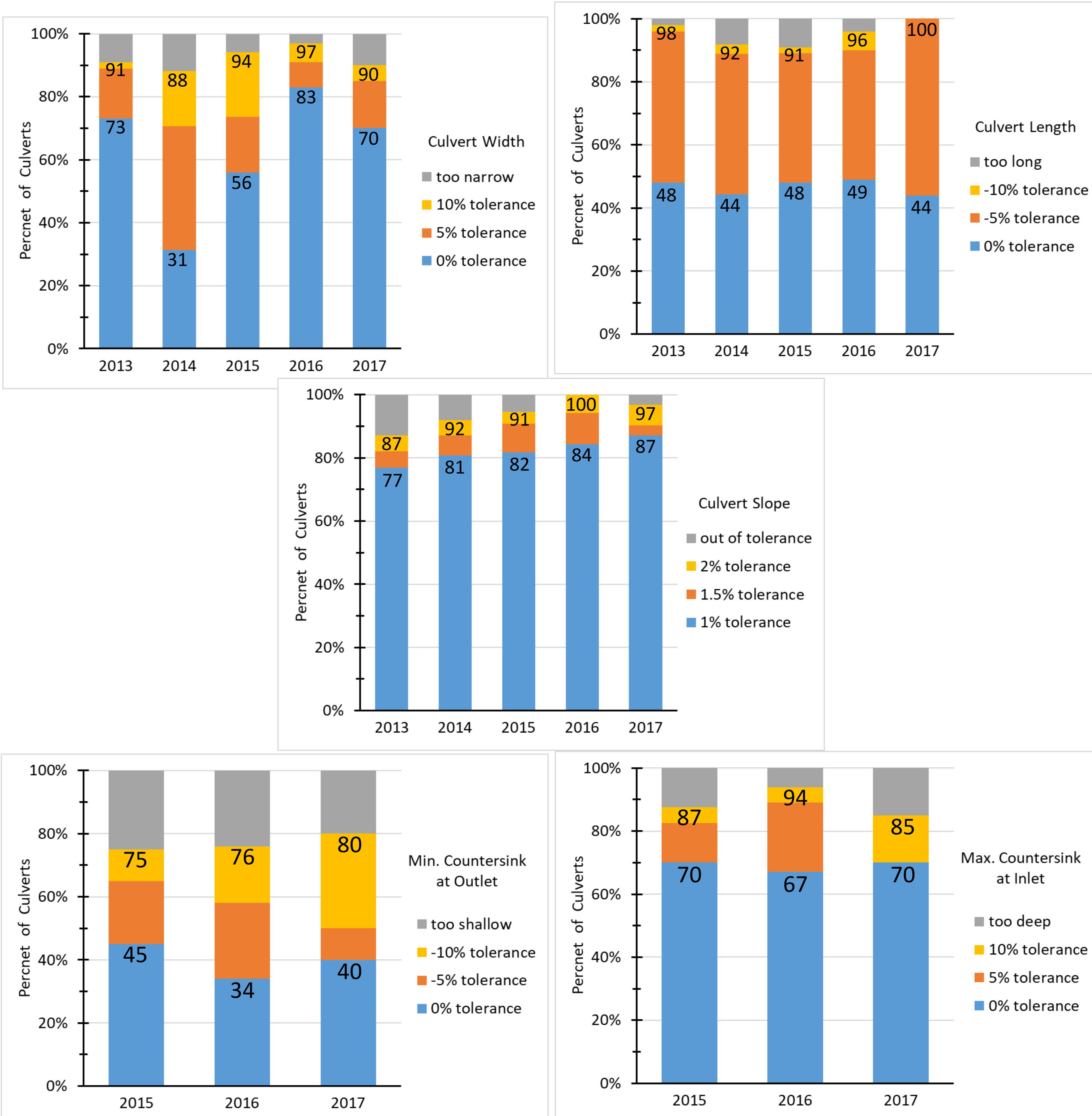

Figure 2.16. Effect of tolerance levels on meeting a permit's specification for each critical structural dimensions. Vertical axis is percent of culverts meeting their permit's specification. For culvert width at streambed and length, tolerance is expressed as a percentage of the specification. For culvert slope and countersinking, tolerance is added to the permit specification. Tolerance for slope is two-sided (i.e., plus or minus). Tolerances for other structural dimensions are one-sided. Too narrow, long, shallow, or deep means that culvert exceeded the largest tolerance presented in this figure. Top number in each column is sum of yellow, orange, and blue sections. Bottom number is percent of culverts for 0% tolerance only.

drawings difficult to interpret. In addition, every engineering firm (maybe every engineer) seems to do drawings differently, and some are not drawn to scale. Consequently, we had to re-decipher nearly every set of drawings. These difficulties reduced the efficiency of our monitoring efforts, and we suspect these same difficulties plague habitat biologists as well. Therefore, for the purposes of permitting, rule enforcement, and monitoring, we recommend that key information – such as bankfull width, channel slope, culvert design type, and culvert dimensions – should be recorded and easy to find. For example, a mandatory form that summarizes key information could be submitted with all HPA applications.

Second, in our progress report for the first year of implementation monitoring (Wilhere et al. 2015), we identified channel width estimates as a potential major problem. That situation has not changed. Figure 2.7 shows wide discrepancies between channel width estimates of permittees and channel width estimates of the implementation monitoring field crew. We presume that estimates done by our own staff were more accurate than those of most HPA permittees. Hence, if permittees' underestimates of channel width were used in culvert design, then many culverts are too narrow. To explore the potential consequences of erroneous channel width estimates on culvert design we did two additional analyses. First, Table 2.10 compares the permitted culvert width at the streambed with the "assumed initial" culvert width of the permittee. The assumed initial culvert width was calculated with the channel width estimate submitted by the permittee in his/her application materials.[27] We use the phrase "assumed initial" culvert width because while there often is no record of culvert design changes that occurred during the permit application process, it is reasonable to assume that the initial culvert width was based on the permittee's channel width estimate. We found that 83% of permitted culvert widths were larger than the assumed initial culvert width. Furthermore, when the assumed initial width was narrower than the permitted width, it was, on average, 2 ft too narrow, and the maximum difference per year between the permitted width and assumed initial width ranged from 6.2 to 12.6 ft. These results indicate that channel width estimates submitted by HPA permit applicants are being corrected during the permit application process, and that some corrections are substantial. Most importantly, corrections to channel width estimates are leading to wider culverts. However, these results are only indicative, not conclusive, because changes to channel width estimates or culvert designs are often not recorded in the HPA application materials or permit documentation.

The second analysis regarding channel width estimates appears in Table 2.11, which compares the permitted culvert width at the streambed with an "expected" culvert width. The "expected" width was calculated with the channel width estimate done by the implementation monitoring field crew. We found that the expected culvert width was wider than the permitted culvert width for 27% of culverts from 2014 to 2017. In addition, when the expected culvert width was wider than the permitted width, it was, on average, 2.4 ft wider, and the maximum difference per year between the expected width and permitted width ranged from 2.4 to 8.9 ft. There are two possible explanations for these results: either 1) our monitoring field crew overestimated channel widths, or 2) some habitat biologists underestimated channel widths or did not verify permittees' channel width estimates. We remain uncertain as to the best explanation.

According to WDFW's Water Crossing Design Guidelines (Barnard et al. 2013, p. 13), bankfull width is by far the most important parameter in culvert design, and therefore, measuring channel width accurately is important. Our analyses show discrepancies in channel width estimates between permittees and our monitoring field crew (Figure 2.7), between habitat biologists and permittees ("initial assumed" culvert width), and between habitat biologists and the monitoring field crew ('expected" culvert width). These discrepancies demonstrate something we already knew – 1) some permit applicants do not know how to

[27] The culvert width equation for stream simulation culverts is: width = 1.2•channel width + 2 ft. The equation for no-slope culverts is width = channel width. Channel width is usually measured as bankfull width, and culvert width is measured at the streambed.

measure channel width, and 2) repeatable, accurate estimates of channel width are difficult to obtain. Issues with channel width estimation should be addressed by: 1) developing a standard procedure for estimating channel width, 2) training appropriate Habitat Program staff based on the new procedure, and 3) offering a similar training to people outside WDFW. As mentioned earlier, our first progress report identified channel width estimates as a potential major problem in culvert design. In response, the Habitat Program's Science Division developed a draft procedure for estimating bankfull width. This draft procedure has been subjected to internal peer review and revised. Wide acceptance of a single standard procedure for channel width estimation should reduce errors, inconsistency, and/or disagreements regarding channel width. Therefore, the next step may be to distribute the draft procedure to sister agencies and major stakeholders for review. In addition, because bankfull width is by far the most important parameter in culvert design, we recommend that an "official" channel width estimate be recorded for every new culvert in APPS or on the HPA permit.

Third, of the five critical structural dimensions, culvert countersink at the outlet had the lowest percentage of culverts meeting their permit specification (40% per year, on average). Even with a 5% tolerance, only 60% of culverts met the permit specification. We believe three factors could contribute to this low success rate. First, there is more than one way to measure culvert countersink. This led to some confusion about measurement of countersink during the first three years of implementation monitoring. The implementation monitoring project relies on the Habitat Program's Fish Passage Barrier Inventory Section (FPBIS) to collect data. Consequently, in 2013, for the first year of implementation monitoring we used the method of FPBIS to measure countersink. FPBIS determines culvert countersink by measuring the depth of streambed sediment at the culvert invert (Figure 2.1). In 2014, we identified certain shortcomings of FPBIS's method and developed a new way to measure countersink. In 2015, we learned that the Habitat Program's Engineering Section measures culvert countersink a third way which we believed to be the best way to measure countersink. Hence, we adopted the engineer's method at that time, and have used it exclusively ever since.

At present, the Habitat Program has two different ways to measure culvert countersink – FPBIS's and the engineers'. At the time of our confusion (2013 through 2015) neither method was documented. WDFW's Water Crossing Design Guidelines (Barnard et al 2013), for instance, do not explain how to measure countersink. We do not know how HPA permittees measure countersink. If permittees, or their contractors, and WDFW measure countersink differently, then that could explain why some culverts did not meet the permit specification for countersink. We could address this problem by 1) revising the Water Crossing Design Guidelines to include an explanation of how to measure countersink, 2) including the measurement of countersink in any training or external presentations regarding culvert design, and 3) defining culvert countersink in the Hydraulic Code Rules.

The second factor which may be contributing to the low percentage of culverts that meet permit specification of culvert countersink is the time between completion of culvert construction and implementation monitoring of that culvert. The time between construction and monitoring ranged from about 1 week to 3 months but was typically about 1 month. During that time, the streambed within the culvert could erode, and, in fact, we expect some sediment to be mobilized after water is allowed to flow through a new culvert. As a result, the streambed's minimum elevation could be lowered, and culvert countersink could be reduced. In 2017, we visited a few culverts several weeks after implementation monitoring had been completed to determine whether the countersink had changed due to erosion. Our observations were inconclusive. A more systematic approach is needed to answer questions about changes to culvert countersink shortly after the completion of culvert construction.

The third factor which may be contributing to the low percentage of culverts that meet permit specification of culvert countersink is the lack of information provided by the Water Crossing Design

Table 2.10. Comparison of permitted culvert width at streambed with assumed initial culvert of permittee, which is based on permittee's channel width estimate. Permittee's channel estimate found on project plans or in various application materials (e.g., JARPA). Average and maximum differences between permit culvert width and assumed initial culvert of permittee calculated only for those culverts for which permitted width was greater than assumed initial culvert of permittee. N is the number of culverts that were known to be stream simulation or no-slope designs, had a specification for culvert width at streambed on its permit or on project plans, and we could find a the permittee's channel width estimate.

	Year				
Statistic	**2014**	**2015**	**2016**	**2017**	**Average**
N	34	19	15	16	21
% of culverts with permitted width greater than assumed initial culvert width of permittee	76	89	87	87	83
% of culverts with permitted width greater than assumed initial culvert width of permittee by more than 10%	35	37	33	25	33
Avg. difference between permit culvert width and assumed initial culvert width of permittee (ft)	1.9	2.3	2.2	1.7	2.0
Max. difference between permit culvert width and assumed initial culvert width of permittee (ft)	6.6	12.6	6.2	10.0	8.5

Table 2.11. Comparison of permitted culvert width at streambed with "expected" culvert width. "Expected" width is the culvert width based on bankfull estimate of implementation monitoring field crew. Average and maximum differences between permit width and "expected" width calculated only for those culverts for which permitted width was less than expected width. N is the number of culverts that were known to be stream simulation or no-slope designs and had a specification for culvert width at streambed on its permit or on project plans.

	Year				
Statistic	**2014**	**2015**	**2016**	**2017**	**Average**
N	41	25	22	19	27
% of culverts with permitted width less than "expected" width	29	20	27	32	27
% of culverts with permitted width less than "expected" width by more than 10%	24	16	18	21	20
Avg. difference between permit width and "expected" width (ft)	-2.3	-1.5	-3.5	-2.8	-2.4
Max. difference between permit width and "expected" width (ft)	-8.9	-2.4	-8.6	-4.9	-6.6

Guidelines on the shape of a culvert's streambed. The design guidelines provide considerable guidance on the channel slope and streambed material inside a culvert, but nothing is said about the channel's cross-sectional shape. When backfilling a countersunk culvert with sediment, the streambed's initial shape is created. Sometimes a thalweg (or a low flow channel) is built into the initial streambed shape during culvert construction. This is WDFW's preferred streambed shape, but the Design Guidelines do not say so. Consequently, the initial shape of channels created within new culverts is sometimes completely flat, and the permittee, or his/her contractor measure countersink from this flat surface. A new flat streambed may be more susceptible to erosion than a new streambed with a thalweg. If we measure countersink after this erosion has occurred, then the culvert may not meet the permit specification for countersink. How the initial streambed shape affects the future channel shape is unknown, and we are addressing that question through effectiveness monitoring.

Another problem with the Water Crossing Design Guidelines that may lead to culverts being improperly countersunk is an error in the guidance. Figure 3.4 in the design guidelines shows the transverse cross-section of a round culvert that is "countersunk 50%." If countersink is measured at the highest elevation of the streambed, then the culvert in the figure is countersunk almost 50%. However, if countersink is measured using the engineers' method, then the culvert is only 29% countersunk. The figure suggests that when a thalweg is part of a streambed's initial shape, the culvert's countersink is measured along the edges of the streambed, where it meets a culvert's walls, not at the thalweg.

The fourth issue identified through implementation monitoring of culverts is meaning of compliance. A closely related issue is the application of engineering or "compliance" tolerances in HPA implementation monitoring. For reasons given in the introduction to this report, we avoided the word "compliance." Instead, we used phrases like "met the permit provision" or "met the permit's specification" to describe, the quality of culvert construction. A strict definition of permit compliance could simply be "culvert cannot exceed specification in the permit provision." If we apply that definition to culvert length, then over the 5 years of monitoring, at least 53% of culverts were noncompliant because they exceeded the length specified on the permit or the project's plans. However, a strict definition of compliance may be unrealistic and unfair. Under a strict definition of compliance, if a culvert with a permitted length of 50 ft is actually 50.1 ft long, then it is noncompliant. If an engineering or compliance tolerance is applied, then that same culvert is compliant. If we apply a 5% tolerance to the permit specification for length, then only 8% of culverts we monitored were noncompliant for length, and in 2017 no culverts were noncompliant for length. The key question is "does it matter"? That is, would an extra 1.2 inches on a 50 ft long culvert matter to fish passage or to natural fluvial processes? If not, then should we institute tolerances for culvert structural dimensions?

A tolerance is the maximum acceptable difference between the actual dimension of a structure and the desired or prescribed value of that dimension. Engineering tolerances take into account the practical limitations that technology imposes on construction and the inexact nature of physical measurements. A compliance tolerance might also take into account the potential impacts of a structure that is built too long, too narrow, or too steep. In other words, compliance tolerances should take in account how accurately a permittee can build a culvert, how accurately the permittor can measure it, and how fish will be affected. "Permit compliance" will be sensitive to tolerances, and therefore, tolerances should be realistic and fair, but permitting process must also ensure that compliant culverts pass fish and maintain habitat.

Tolerance are difficult to specify *a priori*, and hence, as we learn more through implementation and effectiveness monitoring, we may develop reasonable tolerances for each of the five critical structural dimensions. In addition, the Habitat Program's Science Division and Habitat Engineering Section have begun collaboration on a 2D morphodynamic modeling project (see Nelson et al. 2016) that will explore the behavior of culvert designs. Through computer simulation of water and sediment flow through culverts, we can study how different culvert dimensions effect the simulation of fluvial processes and channel morphology. This may provide some insights into proper engineering or compliance tolerances for the critical structural dimensions.

The Monitoring – Permitting Process Interface

The purpose of implementing monitoring is to provide objective feedback that can be used to improve the HPA permitting process. However, implementation monitoring does not monitor the entire process; it collects data only from the process's two immediate tangible outcomes: the permit (and associated documents such as the JARPA and project plans) and the completed structure. The former is produced by the permittor and the latter by the permittee. However, focusing on these outcomes does not tell the whole story.

The HPA permitting process can be complicated. When developing an HPA permit for a culvert, a habitat biologist may need knowledge from a variety of highly technical fields – hydrology, fluvial geomorphology, civil engineering, stream ecology, and fish autecology. Every new culvert is different due to differences in site conditions, roadway requirements, project budgets, etc., and so every culvert's design is somewhat different. Habitat biologists must think about regulatory requirements and project objectives at a site scale within a watershed-scale context, and habitat biologists are now even encouraged to think about the potential impacts of future climate change. Furthermore, a key part of the permitting process is the relationship established between permittor and permittee. A successful outcome (i.e., a culvert that passes fish and maintains natural fluvial processes) is more likely when a good relationship is established. A habitat biologist works with an HPA applicant to design a hydraulic structure that follows guidelines and complies with rules. Good relationships often need ample communication, which can occur face-to-face, over the telephone, or via e-mail. No written record may exist for some of these interactions. Furthermore, unforeseen circumstances can necessitate legitimate 11^{th} –hour changes to a culvert's design, and sometimes these changes are not accurately reflected in the HPA permit or final project plans.

In short, a lot happens in the design, permitting, and construction of a culvert that cannot be measured through implementation monitoring. Some projects may not conform exactly to design guidelines or Hydraulic Code Rules, but nevertheless, are successful because the habitat biologist worked with the HPA applicant to develop the best possible project. What can be gleaned from an HPA permit or project plans does not capture the expertise, reasoning, constraints, and professional relationships that resulted in the completed structure. When considering the results of implementation monitoring, Habitat Program managers should keep in mind that our results miss important aspects of the HPA permitting process.

From 2013 to 2017 we observed overall improvements in permit quality and culvert quality (i.e., quality relative to permit provisions and design guidelines). An important question is why did quality improve? Answers to that question could help us maintain positive trends and address our shortcomings. Unfortunately, implementation monitoring was not designed to answer that question, and therefore, we who only collect and analyze data can only speculate. Over that same time period (2013 to 2017) or shortly before, numerous events occurred that could have affected permit and/or culvert quality. The Habitat Program hired a training coordinator, the Program transitioned from HPMS to APPS, habitat biologists' responsibilities were diversified, Hydraulic Code Rules were revised, the Department of Natural Resources assumed responsibility for HPA permits associated with forest practices, the Culvert Case was front page news, the Habitat Program began HPA monitoring, and new staff, both biologists and managers, were hired. Determining which of these or other events in the Habitat Program may have affected permit or culvert quality is best left to those closer to the HPA permitting process.

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Part 3. Effectiveness Monitoring of Culverts

Introduction

The Washington Department of Fish and Wildlife (WDFW) is a leader in the design of water crossings (i.e., culverts and bridges) that do not impede fish movement. In fact, WDFW is recognized as the inventor of the stream simulation culvert which has been adopted by departments of transportation throughout the United States (Cenderelli et al. 2011). WDFW's main culvert designs, no-slope and stream simulation, have become the predominant designs allowed under the Hydraulic Code Rules (WAC 220-660-190(6)). While the no-slope design has been part of the Hydraulic Code Rules for over 20 years, the stream simulation design has been in the rules since only 2015. Guidelines for both designs were first published in 2003 (Bates et al. 2003).

Current culvert designs (Barnard et al. 2013) are based on the assumption that if a culvert's stream channel imitates the geomorphic and hydraulic characteristics of the natural channel, then it will not develop physical or hydraulic barriers, and consequently, maintain fish passage. This *geomorphic approach* to culvert design allows natural stream processes to occur through the culvert as they do upstream and downstream of the road crossing. When designing a stream crossing, engineers using the geomorphic approach first design the channel based on nearby reaches. They rely heavily on field measurements to estimate the bankfull width, cross-sectional shape and low flow channel depth, appropriate slope through the culvert, as well as sediment sizes that match those found naturally in the stream. Ideally, after an engineer designs the stream channel, he or she chooses the water crossing structure size and type that best accommodates the channel.

The most important parameter of the geomorphic approach to culvert design is bankfull width.[28] No-slope culvert designs are intended for confined (small floodplain), low-gradient small streams (≤10 ft) with a culvert width at the streambed equal to bankfull width. Stream simulation culvert designs are intended for larger confined streams (≤12 ft), and suitable for a range of gradients. Stream simulation culvert width is sized according to 1.2 multiplied by the bankfull width plus 2 feet. This additional width will accommodate benches on either side of the bankfull channel to simulate stream banks allowing for higher flows to overtop them. The resulting energy dissipation reduces the amount of shear stress and scour within and downstream of the culvert, and maintains the continuity of stream power through the channel reach.

The geomorphic approach is a major theoretical advance in the design of water crossings that do not impede fish movement. However, the guidelines for designing no-slope and stream simulation culverts (i.e., Barnard et al. 2013) are hypotheses based on best professional judgment. Consequently, how these culvert designs will actually perform when subjected to a range of flows over many years is unknown. This uncertainty entails risk. One risk is that some culverts designed according to WDFW's guidelines could degrade aquatic habitats and become fish passage barriers. To address this uncertainty we have begun effectiveness monitoring. Effectiveness monitoring will provide information that either confirms the robustness of our culvert designs or indicates how to improve our designs to ensure fish passage. The latter would lead to changes in WDFW's water crossing guidelines (Barnard et al. 2013) or the Hydraulic Code Rules (WAC 220-660).

[28] Bankfull width is measured at the water surface elevation of the bankfull discharge, i.e., where the topographic break between the channel and adjacent floodplain occurs. WDFW's draft bankfull width estimation procedure applies the term bankfull width to both alluvial and non-alluvial channels (Atha and Wilhere 2016).

Effectiveness monitoring will track over time the continuity of stream channel forms through culverts and their capacity to transport water, sediment, and wood over their expected service lives. We assume that immediately after construction, the channel inside and adjacent to properly implemented culverts resembles the channel upstream and downstream from the culvert (similar width, depth, slope, sediments). We further assume that certain changes which may occur over time indicate a culvert is failing to pass water, sediment, or wood. Such changes, if pervasive, would suggest that we need to improve our culvert designs.

A culvert designed using the geomorphic approach is considered effective when it simulates the upstream and downstream channel conditions over its expected service life. However, we are unsure what "simulate" means. That is, we do not know how closely the channel inside the culvert should resemble the upstream and downstream channels outside the culvert. Ideally, average channel conditions inside would be identical to average channel conditions outside. However, this is unlikely to occur due to natural variability and the extreme difficulty of creating channel banks within a culvert. Even if hydraulic and geomorphic processes within a culvert fully simulate the same processes outside the culvert, natural variability will lead to differences between channel conditions inside the culvert and outside the culvert. What amount of difference should be judged "ineffective" is not obvious.

The channel type most appropriate for culverts is a confined, non-meandering channel (Barnard et al. 2013). Importantly, this implies that no-slope and stream simulation designs should be utilized only on stream channels with a narrow floodplain that are in equilibrium. Dynamic equilibrium, first termed by Gilbert (1877), refers to a condition of relative stability that results from the opposing processes of erosion and deposition of sediment. A fluctuating sediment balance may result in drastic changes in channel forms for a period of time, however, on average, the bankfull width and abundance of channel forms remains largely unchanged. Effectiveness monitoring must isolate changes in channel forms that occurred due to the culvert from natural stream channel adjustments that continually occur. In other words, we must determine whether channel conditions within a culvert are within the range of natural variability. While this will be challenging to do, there are characteristic stream channel problems caused by culverts that are detectable through data collection and analysis.

Common Ways Culverts Can Create Fish Passage Barriers

A common problem that causes culverts to become fish passage barriers are undersized culverts that create flow constrictions at the culvert inlet. Commonly, these constrictions increase velocities through the structure causing scour and downstream incision to occur. The result of this scour is often a deep plunge pool at the culvert outlet (Figure 3.1). These plunge pools are deeper than channel depths found in the rest of the reach, and often leave the undersized culvert perched above the downstream channel, making it impassable for migrating organisms (Stream-Simulation Working Group 2008). When the out-flowing water maintains erosive energy downstream of the culvert, it can cause channel and bed degradation for some distance downstream (Kondolf 1997).

Flow constrictions from undersized culverts can cause backwatering effects. Slower stream velocities then result in sediment deposition at the culvert inlet. This channel aggradation directs flow toward the channel banks causing erosion and channel widening. A resulting decrease in gradient due to aggradation will cause more sediment to build up, often causing mid-channel bars to form. Through time this creates what is referred to as the 'dumb bell' planform view (Figure 3.1).

Flow constrictions from undersized culverts, often exacerbated by sediment and debris blockages, can also cause culverts and their associated roadways to act as dams. This causes an increase in the water surface elevation, backwater pools, on the upstream side of the road. Backwater impacts, depending on their extent and duration, can be damaging to streams and adjacent floodplains in addition to human infrastructure.

In addition to channel planform changes, when culverts interrupt the large wood supply, reach-scale channel morphology may also change. Large and stable instream wood creates localized turbulence that erodes banks, scours pools, stores sediment, creates in-channel bars, etc. A decrease of in-stream wood downstream of culverts may have a large effect on the stream channel's sediment storage, hydraulic forces, and resulting channel forms (Montgomery et. al. 2003).

Natural channels exhibit variable bed and bank features that project into the flow of the water, creating roughness that are hallmarks of high habitat complexity (Reeves et al. 1995). These bed and bank features create micro-eddies which provide low velocity areas for many aquatic species (Klingel 2014). Improperly implemented culverts often lack natural substrates, roughness features, and variable channel depths, leading to a reduction in the overall velocity variability, and in particular a reduction in areas of low velocity.

Conversely, when a streambed through a culvert is wider than the natural channel and the bed within the culvert does not contain a properly formed low-flow channel, the flow may spread evenly across the bed, decreasing the water depths through the culvert. This has adverse implications for fish passage. Barnard et al. (2015) found culvert thalweg mean depth to be generally shallower in stream simulation culverts than in the adjacent natural channel. Their study also suggested that, as often constructed, culvert bed shape and slope may not readily change through time, and therefore engineers must pay careful attention to the bed design at the time of project construction.

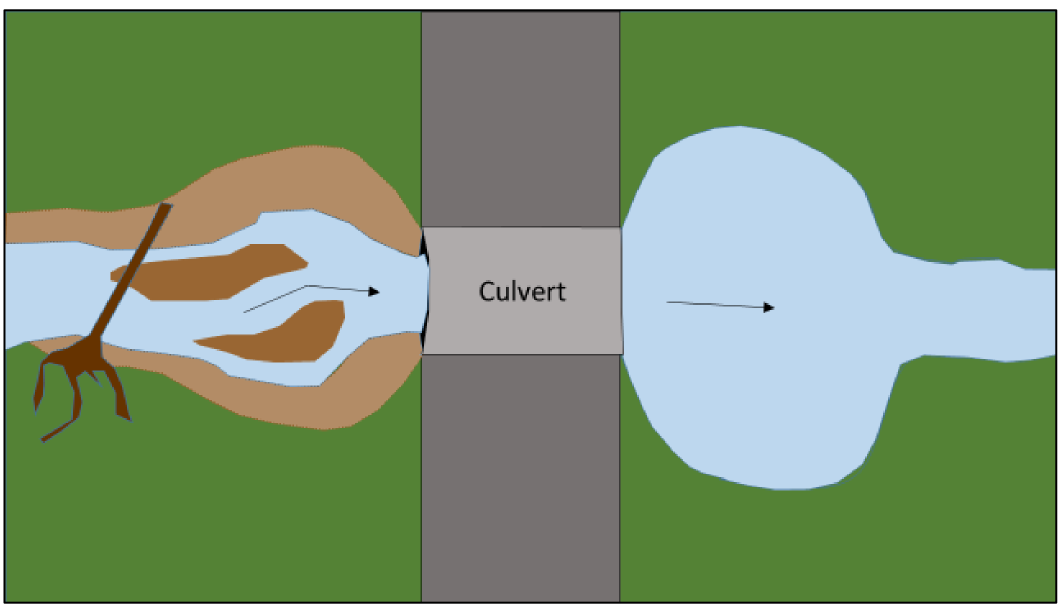

Figure 3.1. Planform view of bed and bank erosion and aggradation caused by an undersized culvert.

Approach to Effectiveness Monitoring

The culverts selected for effectiveness monitoring are those that have a permit issued by WDFW and that correctly implemented the current rules and guidelines for water crossings. These selection criteria focused our limited resources on only those culverts that could teach us about the effectiveness of our current culvert designs and hydraulic code rules. We currently assume that culverts that meet WDFW's standards (i.e., either guidelines or rules) will simulate the stream channel. When we visited culverts shortly after construction, we gathered baseline data that allowed us to compare against future changes in channel conditions. Our aim was to detect adverse changes in the stream channel that signal a culvert is not simulating the channel, and which indicate the culvert is ineffective. The ultimate measure of effectiveness for culverts is whether they continue to simulate the stream channel through long periods of time (>20 years). The purpose of effectiveness monitoring is to learn why culverts are or are not meeting this objective, and to elucidate common characteristics of culverts not meeting design objectives. From there, we can more closely investigate culvert performance to determine how we might improve culvert designs.

We used performance indicators to quantify channel changes of particular importance to culvert performance, such as flow conveyance, aggradation of sediment upstream, and degradation of bed material through the culvert as well as downstream. The indicators are intended to detect adverse changes in hydraulics or channel morphology that can be caused by culverts. They alert us to potential problems such as upstream aggradation or downstream degradation. Yet it is important to consider that sediment aggradation or degradation in a culvert's vicinity can be due to the effects of the new culvert or to natural shifts in bed material. We are interested in detecting large changes that exceed natural variability in the stream channel and exceed variation in measurement precision among years by field technicians. We call such changes "changes of concern" (CoC). However, at present, we do not know appropriate values for changes of concern for any of our indicators, and therefore, we examine a range of potential values in this report.

This report describes the data collected for the first five years of effectiveness monitoring since the project's inception in 2013. Our approach to effectiveness monitoring differs from others (i.e., Stockard and Harris 2005; Bair and Robertson 2010; Klingel 2014) in that it tracks new culverts through time for channel form continuity rather than basing effectiveness on comparison to a nearby reference reach. This report provides the rationale for our data collection and analysis methods, reports on changes to channel form that have occurred primarily in the first year after culvert installation, and discusses some future project directions.

Methods

We visited newly constructed culverts each year from 2013 through 2017, and we refer to these annual groups as cohorts 1 through 5. Field crews first evaluated culverts for correct implementation by collecting key measurements at each site, and comparing them to the permitted culvert dimensions that follow the hydraulic code rules or design guidelines. If a field crew determined that a culvert was implemented correctly, then it was included in effectiveness monitoring. A culvert is implemented correctly when it 1) was approved through an HPA permit, and 2) meets stream simulation or no-slope criteria based on culvert width at the streambed, culvert slope, maximum channel slope, and percent countersink at the culvert inlet and outlet (see Appendix E). Our original intention was to visit culverts in years 1, 2, 5, 10, and 20. These years correspond to intervals of 0, 1, 4, 9, and 19 years after construction, respectively. Field crews visited cohorts 1 through 3 in years 1 and 2, and also revisited cohort 1 in year 5. Due to lack of funding, we did not revisit cohort 4 in year 2. Year 2 visits for cohort 5 and later cohorts will depend on future funding.

The sites are located in western Washington primarily within the Pacific Maritime Ecoregion, with a few sites in the foothills of the Cascades within the Western Cordillera Ecoregion (Figure 3.2). We limited monitoring to western Washington because most new culverts occur in this region and limited resources constrained the number of sites we could visit.

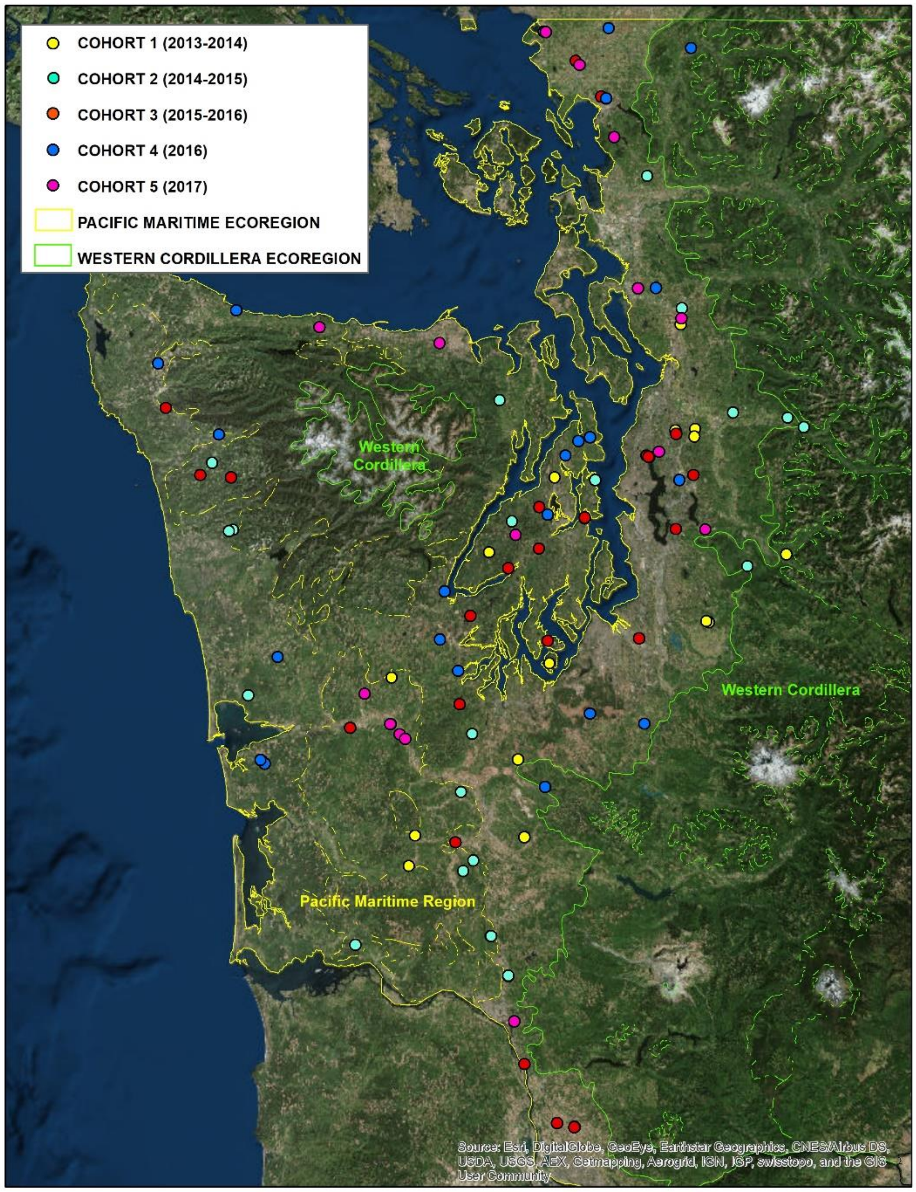

Figure 3.2. Effectiveness monitoring site locations.

Culverts are first evaluated for fish passability according to protocol from WDFW's *Fish Passage and Surface Water Diversion Screening Assessment Manual* (WDFW 2009).[29] WDFW developed the fish passage assessment based on the swimming capabilities of a 6-inch trout. We assume fish passage when there is no barrier due to excessive water drop or velocity, excessive channel slope, shallow flow, lack of

[29] In year 1, the fish passage barrier assessment is done as part of implementation monitoring. In subsequent years, it is done through effectiveness monitoring.

surface flow, lack of bed material, or uncharacteristically coarse bed material. Flow velocities used in the assessment are in the current hydraulic code rules (WAC 220-660-200), and were based on the professional opinion of fish biologists. Field crews conduct a Level A barrier assessment which evaluates hydraulic drop and culvert slope (Figure 3.3). The passability of most culverts is determined through the Level A assessment, however, if a determination cannot be made, then the culvert moves on to a more comprehensive Level B assessment.

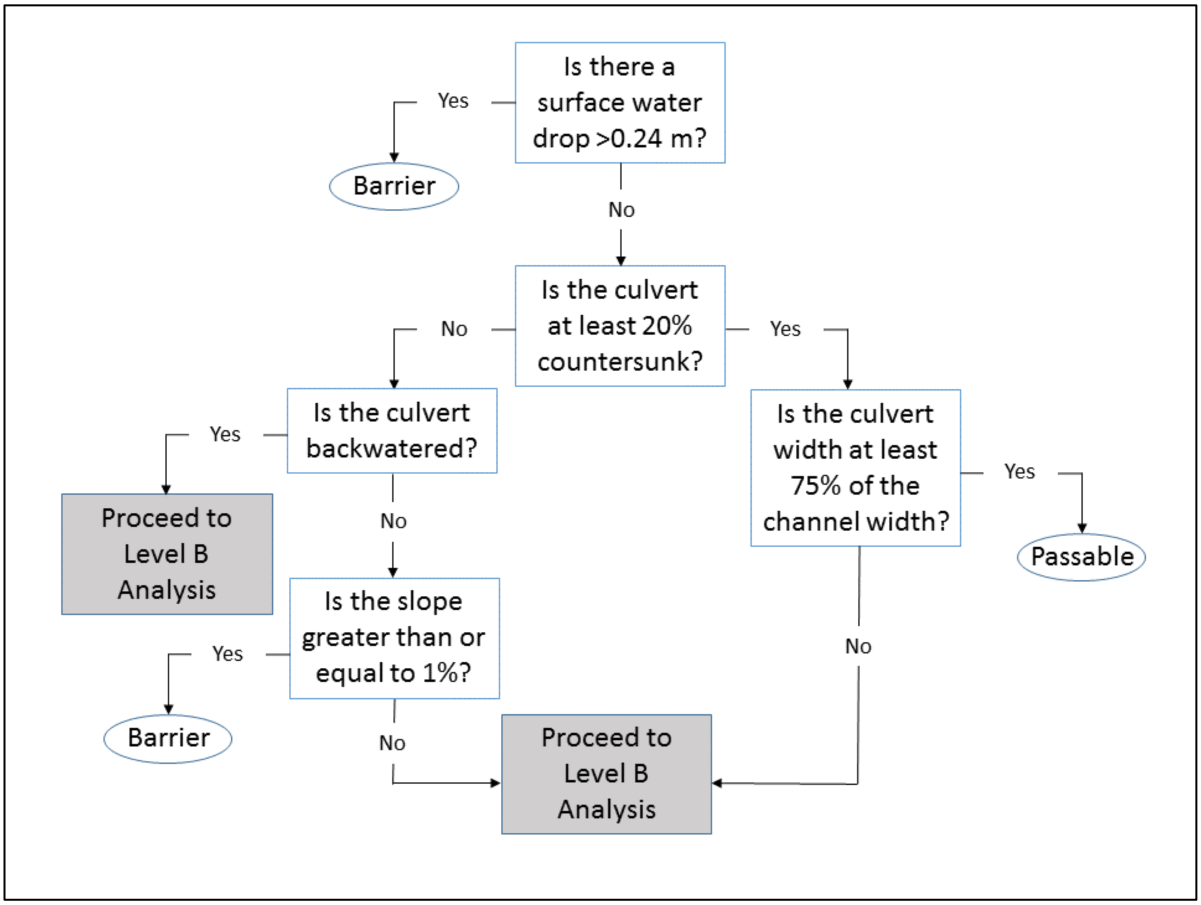

Figure 3.3. Flow chart of the Level A fish passage barrier assessment for culverts (modified from WDFW 2009).

Field crews collect Year 1 effectiveness monitoring data as soon as possible post-construction to ensure that the data best reflects the culvert and stream reach at the time of the installation. This provides confidence that the initial data represent the project as it was constructed, and that any subsequent changes that occur are a result of subsequent stream channel processes. We assume that there is no maintenance or repair on the culverts in the first 5 years. It is also worth noting that there can be a time lag of sometimes up to several months between project construction and effectiveness data collection. We continue to work towards minimizing this time gap.

Our first cohort of culverts began with 14 sites in 2013. Field technicians revisited them all in 2014, however, by 2017 three culverts were no longer available for effectiveness monitoring, reducing our cohort size to 11. One of these culverts we were unable to revisit because the landowner did not give us permission. Another culvert became a debris barrier, was decommissioned, and a replacement bridge in another location was constructed. The third culvert is still in place; however, Snohomish County built a bed material collection box in order to capture and regularly remove excess sediment from the stream bed. The county did this to prevent flooding caused by an abundance of material that has been washing into the stream channel from the adjacent hillside.

The effectiveness monitoring field data collection protocol has been revised two times since 2013 as we have refined analyses and gained efficiencies. When we revisited culverts for Year 2 or Year 5 data collection, we followed the same field protocol as Year 1 for direct comparison. We will follow the same field protocol in Year 10 as well. The current field data collection protocol may be in found in Appendix 1. While the protocols have been modified, the fundamental questions and analyses regarding culvert performance first considered for this work remain unchanged.

We surveyed the culverts using standard survey practices (e.g., Harrelson et al. 1994), and collected data on channel morphometric variables in stream reaches upstream and downstream of the culvert, and when possible, through the culvert structure itself (Table 3.1). These variables included morphological indicators such as channel gradient and channel depth variance, habitat indicators such as pool frequency, pool depth, and presence/absence of large woody debris, and hydraulic indicators such as water depth. Water depth, in addition to telling us what is happening on the day of data collection, may be used to derive velocities from uniform flow equations (e.g., Manning et al. 1891). The number of cross-sections have ranged from 6 to 8, with 3 to 4 placed upstream and downstream of the culvert, spaced approximately 2 to 3 bankfull widths apart, and oriented perpendicular to the thalweg (Figure 3.4). The first cross-section, the farthest upstream, is determined by measuring upstream from the inlet. To re-establish cross-sections in subsequent years, technicians take photographs of each cross-section and identifying markers on the bank (Appendix F).

We have modified the field data collection protocols to decrease the amount of time needed to complete the surveys as well as maximize the utility of the data collected as we have learned more about typical site characteristics. The current protocol includes, where possible, four cross-sections ~2-3 bankfull widths apart depending on stream topography upstream and four cross-sections downstream of the culvert. Along each cross-section, a team of two field technicians measure channel bed elevations. Beginning at the top of bank, one technician with a rotating laser level target attached to a stadia rod identifies significant changes in bed elevation (approximately 0.1m or more) along the cross-section. The technician plants the stadia rod at various locations along the cross-section so that the data capture these changes in bed elevation. The other technician records the elevations on data sheets that include the top of the bank, mid-bank, toe of the bank, and bed elevations across the channel. They continue this process until they reach the top of opposite bank. The number of measurements per cross-section may vary depending on how complex the bed topography is at the site (Figure 3.5).

The length of the longitudinal transect is dependent on the stream's bankfull channel width (BFW). In most cases, we determine the total longitudinal transect length both up and downstream of the culvert by multiplying the measured BFW by 30, similar to other profile survey methods (i.e., Harrelson et al. 1994, Stream-Simulation Working Group 2008). The intent of this method is to help ensure measurement across the typical range of variability observed within a stream reach. For example, measurement along 30 BFW should include measurement of a meander, including at least one riffle-run-pool-glide sequence if they are present. This also helps normalize the data collection length across sites by making length proportional to channel width (Figure 3.6).

The ability to detect changes over time through repeated measurements is affected by measurement precision. We assume that variation in measurements among field technicians due to differences in skill, motivation, and subjective judgment will be smaller than the size of changes that we aim to detect. The channels we measure are not large (bankfull width ~ 3-5 m), but changes of concern in channel form should be comparatively large with respect to the measurement precision. To minimize inter-observer variability, we conduct training on identifying slope breaks and other important elements of cross-sectional contouring and delineation.

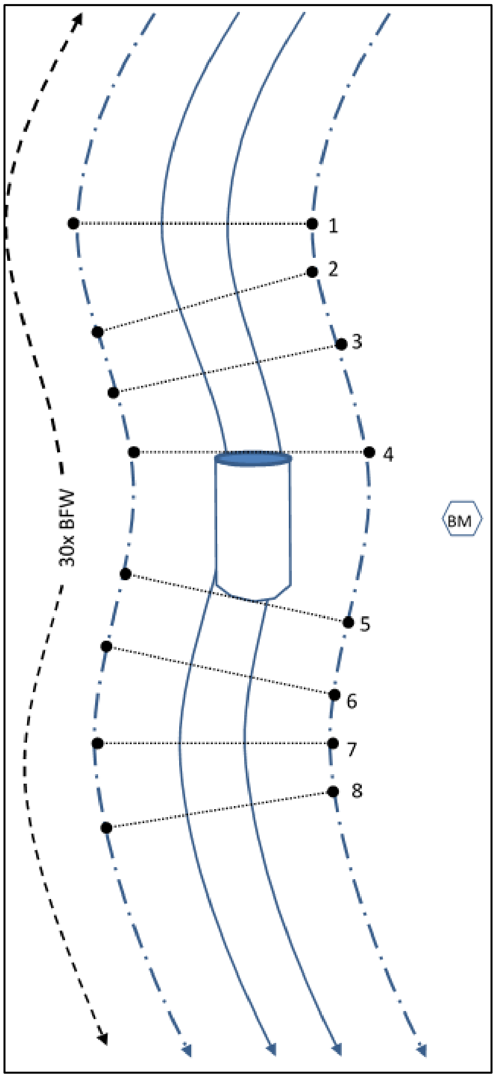

Figure 3.4. Plan view layout of cross-sections surveyed upstream and downstream of culvert. The cross-sections are numbered 1-8 with cross-section one being the farthest upstream. The length of the longitudinal profile for cohorts 3 to 5 was 30 times BFW as indicated above. Longitudinal profiles not done for cohorts 1 and 2. BM represents the benchmark location, usually established on the side of the road.

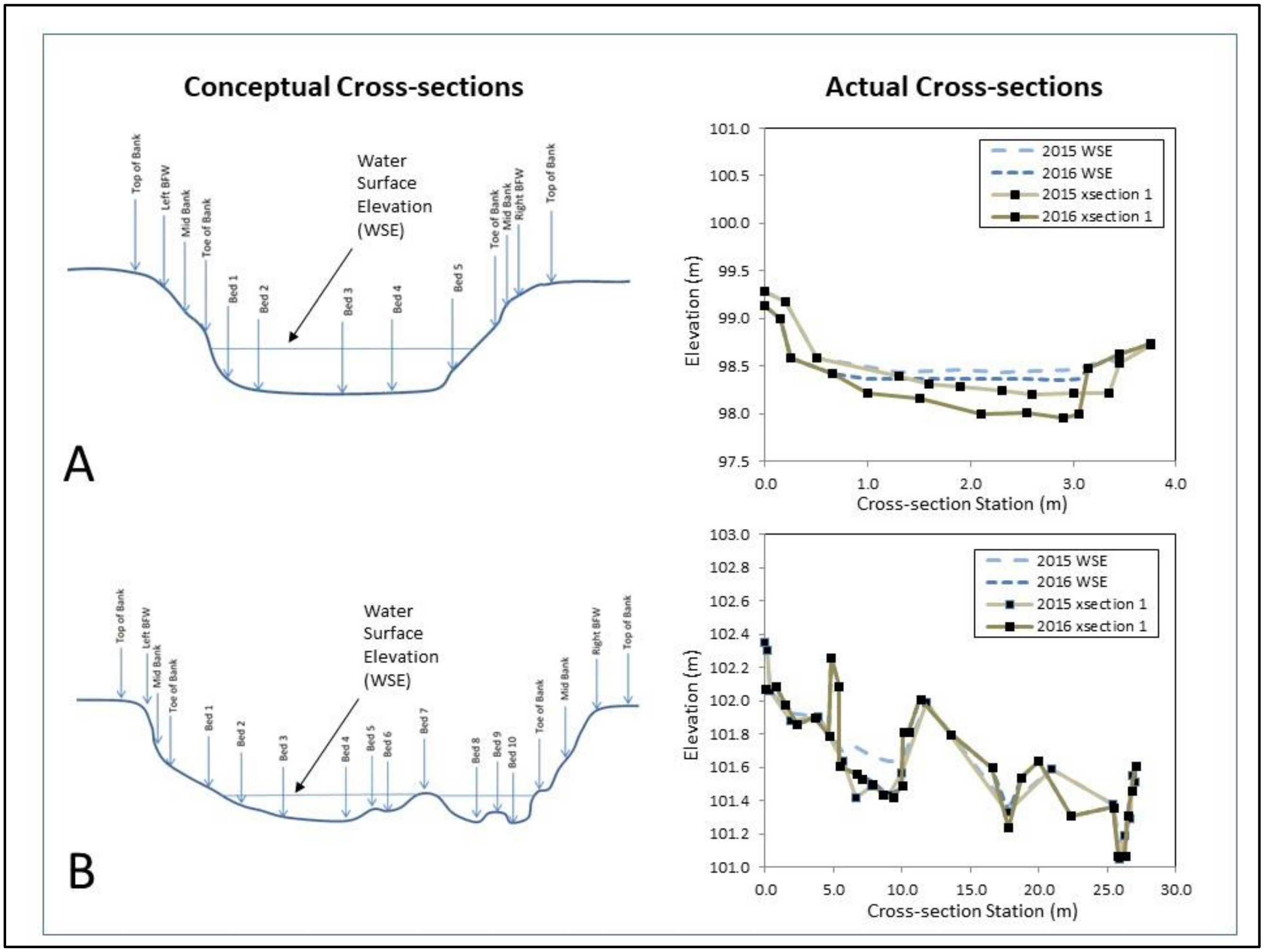

Figure 3.5. The figures on the left are conceptual layout examples of stream survey cross-section elevation measurements with (A) a relatively flat channel bed, and (B) a more complex channel bed. The arrows indicate where elevation measurements are taken. The figures on the right are actual cross-sections measured at sites that display the relative elevation data on the y-axis, and the cross-section station location on the x-axis. The blue dashed lines show the water surface elevation (WSE) for the two years.

Table 3.1. Transect measurements and parameter estimates from data collected at culvert sites.

Transect Measurement (units)	Characteristics
Longitudinal profile of culvert reach (m/m)	Elevation measurements taken at the riffle crests (location in a riffle with the highest elevation), lowest pool elevations, and the tail-out of pools along thalweg for 30 x BFW
Culvert long profile (m/m)	11 evenly spaced measurements along thalweg within the culvert
Bed elevations (m)	Multiple measurements taken at 6 total cross-sections, 3 upstream and 3 downstream, 2-3 bankfull width apart
Water depth (m) at time of site visit	Taken with every bed elevation measurement along each cross-section

Parameter (units)	Characteristics
Mean Bankfull width (m)	4 total field measurements, 2 upstream and 2 downstream at representative locations
Mean Bankfull depth (m)	Average of measurements from 4 cross-sections, 2 upstream and 2 downstream. Depth is the difference between the thalweg elevation and the average of bankfull edge elevations from the left and right banks.
Slope (m/m)	Derived from rise/run of thalweg elevations at uppermost and lowermost cross-sections
Culvert substrate (mm)	Measured at left bank, right bank, and thalweg at 11 evenly spaced increments
Substrate (mm)	Categorized into 13 size classes. One substrate sample taken at each station location along 6 cross-sections, 3 upstream and 3 downstream
Backwater elevation (m)	The highest observable water line upstream of the culvert
Total Pool frequency (counts)	Counted between the 6 cross-sections upstream and downstream of the culvert
Total Large woody debris (counts)	Counted between the 6 cross-sections upstream and downstream of the culvert. Minimum size criteria: diameter ≥ 30cm, length ≥ 1m

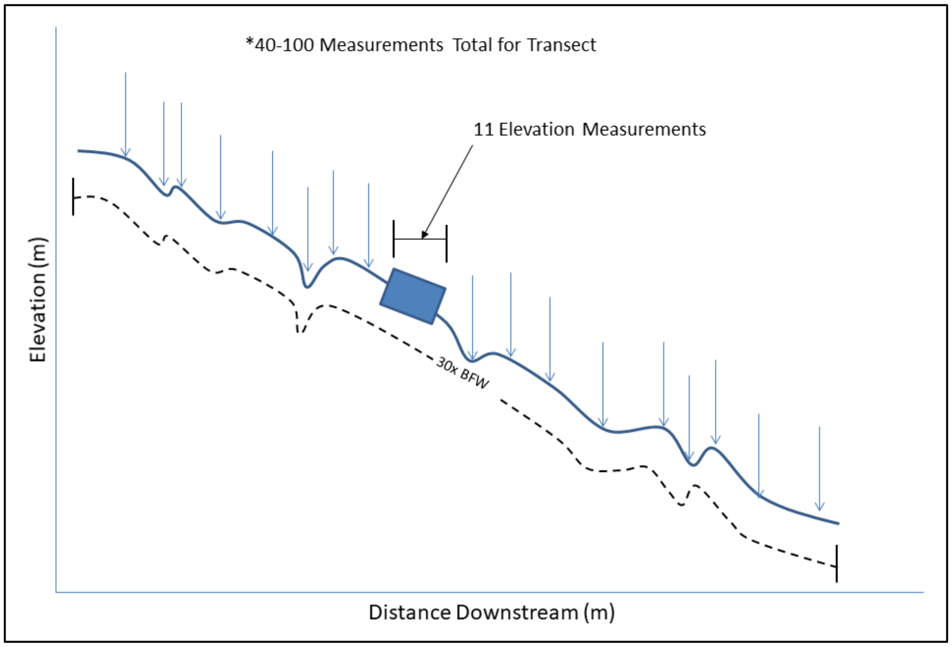

Figure 3.6. Conceptual layout for longitudinal profile elevation measurements. The blue arrows indicate the locations of thalweg elevation measurements.

Culvert Performance Indicators

Culvert performance indicators are derived from measurements taken at the channel cross sections and along the longitudinal transect. The indicators alert us to potentially adverse changes that, if persistent through time, would cause a permanent discontinuity in geomorphic processes and a blockage to fish passage. Change in an indicator becomes a change of concern (CoC) when it exceeds a certain threshold. At present, we do not know for any of the indicators the threshold of change that should be considered a CoC. We examined the sensitivity of several indicators to this threshold (represented by the parameter C_x) by calculating the number of culverts that would exhibit a CoC over a range of CoC thresholds. The range of CoC thresholds used for the sensitivity analysis were based on professional judgment and are preliminary. We anticipate that CoC thresholds will be established and further refined as we learn more about culvert performance through effectiveness monitoring.

Indicator 1. Backwater elevation

This indicator compares the backwater elevation, measured at the highest observable water line upstream of the culvert, to the elevation of the top of the culvert's inlet. Backwatering occurs when a culvert is too small to convey flood flows causing the water surface elevation upstream of the road to rise (Figure 3.7). Field crews detect backwater in periods of low flow by the highest observable water lines upstream of the culvert.

Indicator 1, CoC: $E_{bw} \geq E_{inlet}$

where E_{bw} is the measured elevation of the backwater.

E_{inlet} is the elevation of the top of the culvert inlet.

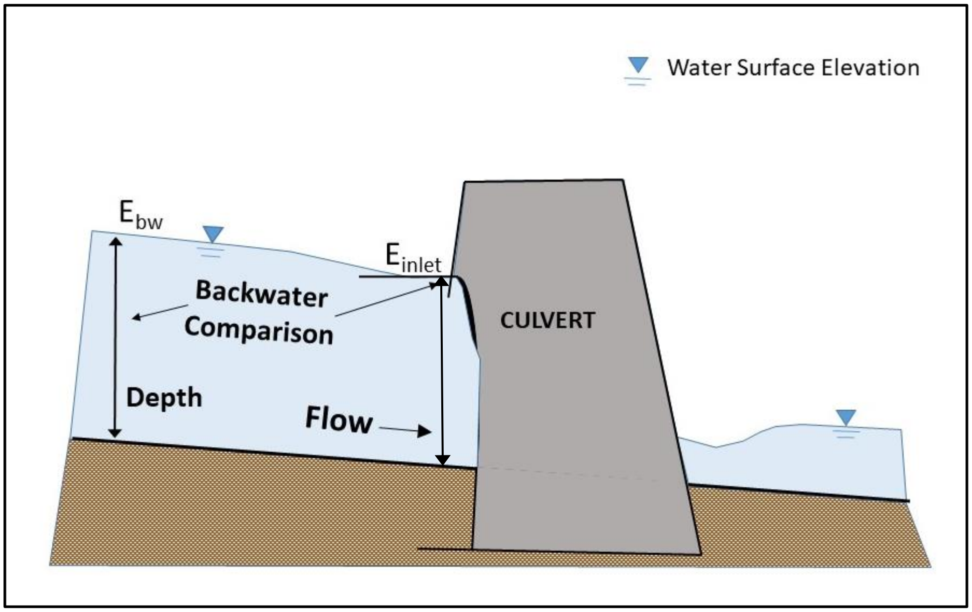

Figure 3.7. Culvert profile illustration of backwater upstream of the inlet.

Indicator 2. Upstream mid-channel bar

Upstream aggradation of sediment in the form of mid-channel bars indicates that the culvert is causing sediment deposition during flood events. To track development of these bars, we calculate the difference between the mean mid-channel elevations and the mean elevations of the left and right bank toes at each upstream cross section (Figure 3.8). We then compare the mean upstream elevation differences at two times (e.g., Year 1 and Year 2). We also calculate the difference between the mean of the mid-channel bar, defined here as the three highest elevations of the channel bed, with the mean channel elevations (not including the bar) and compare them at two times. We evaluate the difference between the mid-channel elevation and channel toe elevations of the later year at changes of 10, 20, 30, 40 and 50% than the earlier year (Indicator 2a) and the difference between the bar elevation and channel bed elevation of the later year at changes of 10, 20, 30, 40 and 50% than the earlier year (Indicator 2b) to assess potential problems at the culvert inlet.

Indicator 2a, CoC: $(\overline{E}_{toe} - \overline{E}_{mid})_{t1+i} \leq C_{2a} (\overline{E}_{toe} - \overline{E}_{mid})_{t1}$

where $\overline{E}_{toe}$ is the mean elevation of the toe the left and right banks.

$\overline{E}_{mid}$ is the mean elevation of the mid-channel bed, where mid-channel is defined as midway between the right and left bank toes.

$\overline{E}_{mid}$ is subtracted from the $\overline{E}_{toe}$ at each of the upstream cross-sections, and then the mean differences are averaged. The later year is compared to the earlier year. If the elevation change is increasing, it indicates that later year bank toe elevations are higher than the mid-channel bed elevations. If it is decreasing, the mid-channel beds are higher or are moving upwards towards the bank toes indicating a potential problem.

C_{2a} determines the threshold for change of concern.

Indicator 2b, CoC: $(\overline{E}_{bed} - \overline{E}_{bar})_{t1+i} \leq C_{2b} (\overline{E}_{bed} - \overline{E}_{bar})_{t1}$

where $\overline{E}_{bar}$ is the mean elevation of a mid-channel bar where the bar is an elevated region of deposited sediment described by three highest, adjacent elevation measurements.

$\overline{E}_{bed}$ is the cross-sectional average of the mean elevations of the channel bed as measured from the right to left toe of bank, not including the elevations used to measure the bar. $\overline{E}_{bar}$ is subtracted from the $\overline{E}_{bed}$ at each of the upstream cross-sections, and then the mean differences are averaged. The later year is compared to the earlier year. If the elevation change is increasing between years, it indicates that later year bed elevations are higher than the mid-channel bar elevations. If it is decreasing, the mid-channel bar is increasing relative to the channel bed indicating a potential problem.
C_{2b} determines the threshold for change of concern.

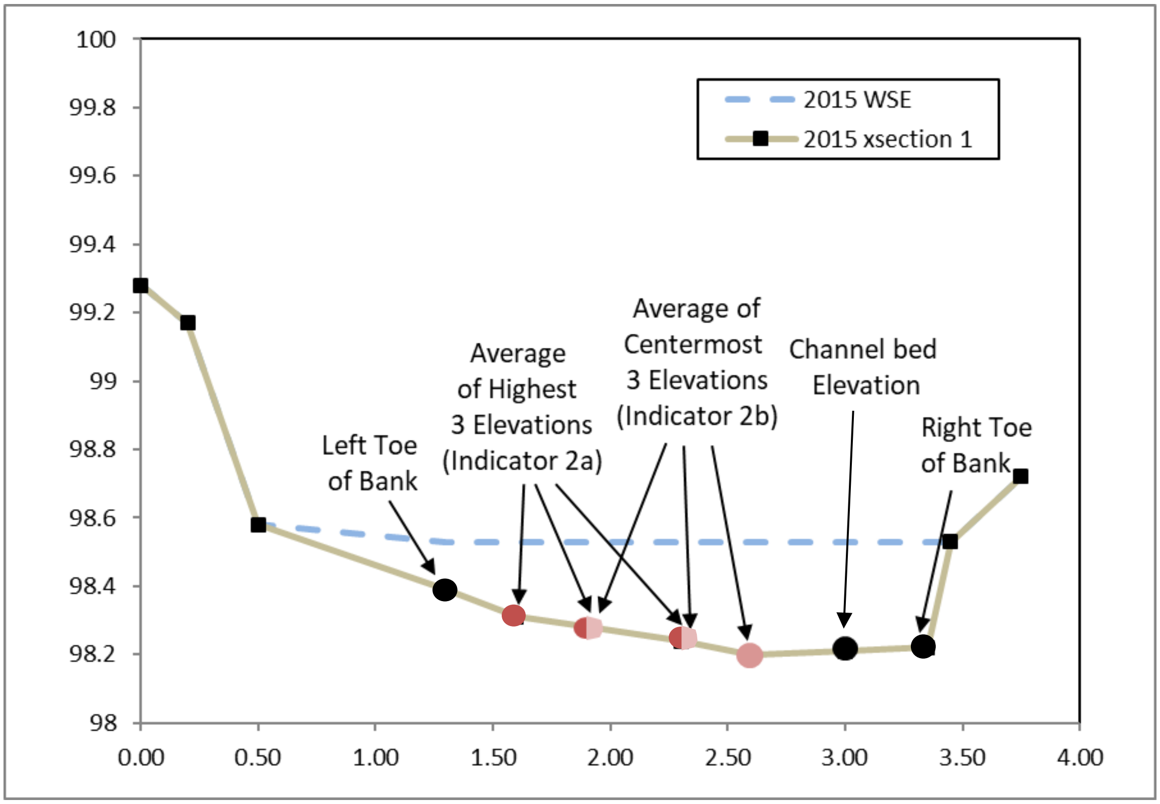

Figure 3.8. Cross-section depicting the highest mid-channel elevations, the centermost channel elevations, and the left and right toe of the banks. The tan line is the channel bed cross-section, and the blue dashed line is the water surface elevation. The elevations are based on an assumed coordinate system with a 100.00 meter benchmark. For indicator 2a the average of the centermost 3 elevations is subtracted from the average of the left and right bank toes. For indicator 2b, the 3 highest elevations are subtracted from the mean elevations of the channel bed including the bank toes.

Indicator 3. Downstream mid-channel trough

Decreases in channel elevations downstream of the culvert indicate channel scour due to increased velocities through the culvert or low substrate transport. To track the development of downstream troughs, we calculated the differences between the elevations of the three lowest, adjacent elevation measurements near the center of the channel and the mean elevations of the channel bed between the left and right bank toes (Figure 3.9). We then compared the mean downstream elevation differences between two times (e.g., Years 1 and 2). We evaluate the difference between these elevations at increases of 10, 20, 30, 40 and 50% with the later year to assess potential problems at the culvert outlet.

Indicator 3, CoC: $(\overline{E}_{bed} - \overline{E}_{trough})_{t1+1} \geq C_3 (\overline{E}_{bed} - \overline{E}_{trough})_{t1}$

where $\overline{E}_{trough}$ is the mean elevation of the mid-channel trough, where the trough is defined as the three lowest, adjacent elevation measurements in the channel bed.

$\overline{E}_{bed}$ is the cross-sectional average of the mean measured elevations of the channel as measured from the right to left toe of bank, not including the elevations used to measure the trough.

C_3 determines the threshold for change of concern.

Indicator 4. Cross-sectional depth variance

This indicator compares elevational variability between two years among all cross-sections. It indicates if channels upstream are flattening through time, and it also indicates if channels are deepening downstream of the culvert indicating incision (e.g., Olson-Rutz and Marlow 1992). We calculated a Gini coefficient for each upstream cross-section, and then averaged the 3 Gini coefficients. We compared the mean Gini coefficients from Year 1 and Year 2 (indicator 4a). We did the same calculations for the downstream cross-sections (indicator 4b). For Cohort 1 we also compared Year 2 with Year 5. The Gini coefficient is non-dimensional, ranging from 0-1, and reflects the amount of variability in elevation within each cross-section. It approaches a minimum value of 0 when all depths are equal indicating a flat channel. The Gini coefficient approaches its maximum value of 1 when the channel is deep and narrow (Olson-Rutz and Marlow 1992). For Indicator 4a, Y_i is each depth (i.e., elevation) measurement along the streambed, and n is the number of Y_i values measured along the cross section. The Gini coefficient is the arithmetic average of the differences between all pairs of depths $(Y_i - Y_j)$:

$$G = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} |Y_i - Y_j|}{2_n 2\bar{Y}} \quad (1)$$

We highlight changes of concern upstream if the Gini coefficient is decreasing (getting flatter), and conversely, we consider it a change of concern downstream if the coefficient is increasing (becoming more incised). We compare changes of 10-50% between years from to detect changes of concern.

Indicator 4a, CoC: $\overline{G}_{upstream,\ t1+i} < C_{4a} (\overline{G}_{upstream,\ t1})$

where $\overline{G}_{upstream,\ t1}$ is the mean of all upstream cross section Gini coefficients at year one.

$\overline{G}_{upstream,\ t1+i}$ is the mean of all upstream cross section Gini coefficients at a subsequent year.

C_{4a} determines the threshold for change of concern.

Indicator 4b, CoC: $\overline{G}_{downstream,\ t1+i} > C_{4b} (\overline{G}_{downstream,\ t1})$

where $\overline{G}_{downstream,\ t1}$ is the mean of all downstream cross section Gini coefficients at year one.

$\overline{G}_{downstream,\ t1+i}$ is the mean of all upstream cross section Gini coefficients at a subsequent year.

C_{4b} determines the threshold for change of concern.

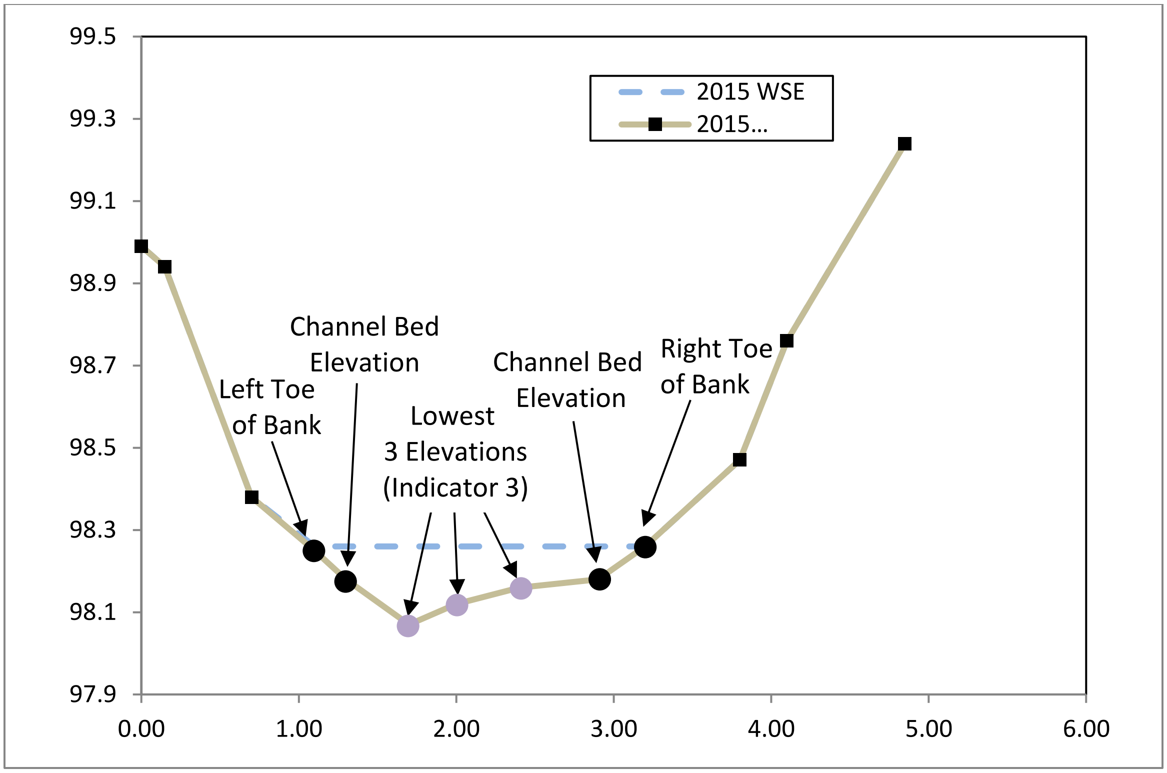

Figure 3.9. Cross-section depicting the lowest mid-channel elevations, channel bed elevations, and the left and right toe of the banks. The tan line is the channel bed cross-section, and the blue dashed line is the water surface elevation. The elevations are based on an assumed coordinate system with a 100.00 meter benchmark. For indicator 3, the 3 lowest elevations are subtracted from the mean elevations of the channel bed including the bank toes.

Indicator 5. Gradient changes

We compared changes in thalweg gradient both upstream and downstream of the culvert (Indicators 5a and 5d, respectively). The upstream channel gradient is measured as the difference between the thalweg elevation at the farthest upstream cross-section, and the thalweg elevation at the cross-section nearest the culvert inlet divided by the horizontal distance between the two cross sections. Similar measurements and calculations are done for the downstream channel gradient. We compare changes between years from 10-50% to detect changes of concern.

Indicator 5a, CoC: $T_{upstream,\ t1} > C_{5a}\ (T_{upstream,\ t1+i})$

where $T_{upstream,\ t1}$ is the channel gradient at year one.

$T_{upstream,\ t1+i}$ is the channel gradient in a subsequent year, and C_{5a} is set to a decrease of 10 to 50% of the original gradient.

C_{5a} determines the threshold for change of concern.

Indicator 5b, CoC: $T_{downstream,\ t1} < C_{5b}\ (T_{downstream,\ t1+i})$

where $T_{downstream,\ t1}$ is the channel gradient at year one.

$T_{downstream,\ t1+i}$ is the channel gradient in a subsequent year, and C_{5b} is set to an increase of 10 to 50% of the original gradient.

C_{5b} determines the threshold for change of concern.

Indicator 6. Pool frequency

We tracked pool frequency through time by comparing the total number of pools through time both upstream and downstream of the culvert (indicators 6a and 6b, respectively). We consider any decrease in the number of pools a change of concern.

Indicator 6a, CoC: $P_{upstream,\ t1} > P_{upstream,\ t1+i}$

where $P_{upstream,\ t1}$ is the count of pools between cross-sections 1 and 4 at time 1.
$P_{upstream,\ t1+i}$ is the count of pools between cross-sections 1 and 4 during subsequent years.

Indicator 6b, CoC: $P_{downstream,\ t1} > P_{downstream,\ t1+i}$,

where $P_{downstream,\ t1}$ is the count of pools between cross-sections 5 and 8 at time 1.
$P_{downstream,\ t1+i}$ is the count of pools between cross-sections 5 and 8 during subsequent years.

Indicator 7. Pool depth

We tracked pool depth through time by measuring and comparing pool depths both upstream and downstream between Years 1 and 2 (Indicators 7a and 7b, respectively). We currently consider any decrease in the pool depths as a change of concern.

Indicator 7a, CoC: $\overline{P}_{upstream,\ t1} > \overline{P}_{upstream,\ t1+i}$,

where $\overline{P}_{upstream,\ t1}$ is the mean pool depth upstream of the project during year one.
$\overline{P}_{upstream,\ t1+i}$ is mean pool depth upstream of the project during subsequent years.

Indicator 7b, CoC: $\overline{P}_{downstream,\ t1} > \overline{P}_{downstream,\ t1+i}$,

where $\overline{P}_{downstream,\ t1}$ is the mean pool depth downstream of the project during year one.
$\overline{P}_{downstream,\ t1+i}$ is the mean pool depth downstream of the project during subsequent years.

Indicator 8. Large wood

We tracked the presence of large wood at each site. We compared large wood counts both upstream and downstream of the culvert site (Indicators 8a and 8b). Currently, we consider any change in the amount of large wood as a change of concern.

Indicator 8a: $LWD_{upstream,\ t1} > LWD_{upstream,\ t1+i}$, where

where $LWD_{upstream,\ t1}$ is the count of LWD between cross-sections 1 and 4 at time 1.
$LWD_{upstream,\ t1+i}$ is the count of LWD between cross-sections 1 and 4 during subsequent years.

Indicator 8b: $LWD_{downstream,\ t1} > LWD_{downstream,\ t1+i}$, where

where $LWD_{downstream,\ t1}$ is the count of LWD between cross-sections 5 and 8 at time 1.
$LWD_{downstream,\ t1+i}$ is the count of LWD between cross-sections 5 and 8 during subsequent years.

Substrate comparisons

We additionally compared changes in substrate size to detect coarsening or fining that may be occurring at each site. This analysis evolved from the results found in Barnard et. al. (2015) as well as anecdotal evidence seen at many culverts, that bed flattening and substrate coarsening has been occurring within culverts through time.

For each year and at each site, field technicians blindly picked up one piece of substrate from the channel bed at each station along a cross-section and noted its substrate size class (Table 3.2). For our analysis, substrate samples from each cross-section station were compared between years, and we noted whether it was finer, coarser, or no change. Next, using the numeric codes assigned to size classes, we averaged the change across each cross section to determine the overall percent change in sediment size between the two years at each site.

Table 3.2. Substrate size classes. The numeric code are numbers assigned to each categorical variable based on relative size.

Size Class	Code	Size Range (mm)	Numeric code
bedrock; smooth	RS	> 4000	7
bedrock; rough	RR	> 4000	7
boulder	BL	250-4000	6
cobble	CB	64-250	5
coarse gravel	GC	16-64	4
fine gravel	GF	2 - 16	3
sand	SA	0.06-2	2
silt/clay/muck	FN	<0.06	1
hardpan	HP	> 4000	7
vegetated organic	VO	16-64	4
wood	WD	> 1000	7
rip rap	RP	250-4000	6
other	OT		-

Additionally, when possible we compared changes in substrate within the culverts. For this analysis we assigned a number to each corresponding size class to compare overall sediment changes between years through the culvert structures (Table 3.2). It was not possible to collect substrate data through every culvert because of safety concerns or small culvert size.

Statistical Analysis

We calculated the mean change between years for every culvert performance indicator. We did the calculations for cohorts separately and for the cohorts lumped together. We calculated the mean change in culvert performance indicators separately for culvert design types too. Because we do not yet know the CoC threshold for each of the indicators, we assessed indicators 2a, 2b, 3, 4a, 4b, 5a, and 5b at thresholds corresponding to 10, 20, 30, 40, and 50 percent change. For each performance indicator and for each CoC threshold we calculated the percent of all culverts that exhibited a change of concern. We did this by culvert design type as well.

Our data were not collected through a random sample, and our cohort sizes are small. Consequently, our data do not satisfy the standard assumptions of parametric statistical tests. Fortunately, randomization methods (also known as permutation methods) enable statistical tests on groups that were not randomly sampled or violate other assumptions required by parametric tests (Ludbrook and Dudley 1998, Ernst 2004). We employed randomization tests to detect statistically significant changes in culvert performance indicators between years. That is, we tested the null hypothesis: mean of Indicator A at time 2 = mean of Indicator A at time 1. Randomization tests of null hypotheses are based on the following logic: if the null hypothesis is true, then a time 2 measurement is just as likely to be larger than a time 1 measurement as it is to be smaller. Statistically, if the null hypothesis is true, a permutation within any pair of scores is as likely as the reverse (Howell 2010, p. 666). Inferences from randomization tests are limited to the individuals that comprise a study (Ernst 2004). However, logical inferences might be made to larger populations with similar characteristics (Ludbrook and Dudley 1998).

Within the R statistical computing package (R Core Team 2013), we ran randomization tests for matched samples by generating permutations of all the possible combinations of the paired data (e.g., Year 1 and Year 2 pairs). We did this for each indicator. Next, the script compared the observed statistic (e.g., mean difference between Year 1 and Year 2) of the original data with the newly generated theoretical distribution and calculated a *p* value. The *p* value from a randomization test is the probability that the results of a study were due to chance. By comparing this *p* value to a subjectively chosen significance level, the result indicates statistically significant changes between years (see Howell 2010, pp. 665-668).

For each indicator we also used randomization methods to test whether the culvert design type affected the percentage of culverts with changes of concern. We applied randomization methods to contingency tables with one fixed marginal (Howell 2009, 2011). The contingency tables were the following form:

		specification		**total of**
		CoC	**no CoC**	**rows**
Permit	**no-slope**	*a*	*c*	*a + c*
	stream simulation	*b*	*d*	*b + d*
	total of columns	*a + b*	*c + d*	

where *a*, *b*, *c*, and *d* are frequencies (i.e., counts). Because we visited almost every new culvert each year and monitored every culvert we determined was properly implemented, we assumed that the row totals were fixed. Randomization involved simulating with a Monte Carlo method possible pairings of *a* and *c* and of *b* and *d* that equaled the fixed row totals. For each randomized contingency table, the χ^2 statistic was calculated.[30] We determined the proportion of randomized χ^2 that were greater than the observed χ^2. This proportion is the *p* value.

The threshold for statistical significance, known as α, is subjective. A commonly adopted threshold is $p <$ 0.05, however, $p < 0.10$ is preferred by some scientists. We report when either of these thresholds were met by a statistical test.

To analyze the data for correlations that may exist between performance indicators, we created correlation matrices for all of the culverts in Cohorts 1-3 for Years 1 and 2. We looked for statistically significant correlations between all pairs of indicators with randomization tests (Howell 2015). Correlation matrices can help to identify relationships between indicators.

[30] $\chi^2 = \sum (O_i - E_i)^2 / E_i$, where *O* and *E* are observed and expected frequencies, respectively, and *i* refers to cells in a contingency table.

Results

The average number of culverts monitored each year for the first time post-construction was 21, ranging from 14 to 27 per year (Table 3.3). The number of culverts that began effectiveness monitoring was reduced for Cohort 1 at Year 5, with 11 of the original 14 still applicable for the study. The average bankfull width of the projects monitored for effectiveness was 3 meters (9.8 ft), and the most common structure type was a bottomless arch culvert.[31]

Fish Passage Barrier Assessments

Culverts monitored for effectiveness have passed the Level A assessment for fish passage in years 1, 2, and 5. We have not yet had to conduct a Level B assessment for any culvert in the effectiveness monitoring project.

Culvert Performance Indicators

The combined average values for cohorts 1-5 show the range of results from Year 1 data collection and analysis for each of the indicators (Table 3.4). The values for indicators 2a, 2b, and 3 are the elevation differences between the bank toes (2a) or channels (2b and 3) and center elevations. These differences range from 0.0004 to 0.49 feet.

Table 3.3. Characteristics of effectiveness monitoring cohorts. The numbers in parentheses in the Cohort 1 row represent the sample size for the Year 5 data. The parentheses in the bankfull width columns are in feet. NS = no-slope culvert, SS= stream simulation culvert.

Co-hort	Years of Data	Num. of Culverts	Design Type			Structure Type					Bankfull Width m (ft)		
			NS	SS	Oth	Squash	Box	Round	Arch	Ellipse	Min.	Max.	Avg.
1	2013, 2014, (2017)	14 (11)	6 (5)	8 (6)	0	5 (4)	4 (3)	0	5 (4)	0	1.4 (5.3)	5.1 (19.5)	3.0 (11.5)
2	2014, 2015	22	6	16	0	2	3	7	9	1	1.4 (5.3)	5.1 (19.5)	2.6 (10.0)
3	2015, 2016	27	8	19	0	3	7	3	13	1	0.9 (3.5)	4.8 (18.4)	3.1 (11.8)
4	2016	25	1	16	8*	1	12	1	10	0	1.8 (5.9)	8.0 (26.2)	4.04 (13.3)
5	2017	17	3	14	0	2	5	2	8	0	1.54 (5.1)	5.44 (17.9)	3.37 (11.1)
All	2013-2017	105	17	87	8	13	31	13	45	2	0.9 (3.5)	8.0 (26.2)	3.22 (10.6)

* These culverts were not classified as no-slope or stream simulation on their HPA permits or associated project plans, but that their dimensions conformed to either no-slope of stream simulation design guidelines.

[31] Bottomless "arch" culverts can be either a rectangular box or a true arch.

Table 3.4. Mean values and standards deviations for each indicator at Year 1. Backwater information was not collected in 2013, and are therefore not available below. Cohorts 4 and 5, beginning in 2016 and 2017 respectively, follow revised protocols that no longer collect pool counts and pool depths and are therefore also not available below. (These data are now captured in longitudinal profiles.)

Indicator	**Description (units)**	**Year 1 Values** Mean (Standard Deviation)					
		2013	2014	2015	2016	2017	All
1	year 2 backwater	na	-0.68 (0.549)	-1.04 (0.739)	-0.97 0.368	-1.53 0.589	-1.00 0.645
2a	mid-channel bar (m)	0.123 (0.078)	0.151 (0.098)	0.077 (0.102)	0.146 (0.098)	0.158 (0.108)	0.131 (0.097)
2b	mid-channel bar (m)	-0.021 (0.049)	-0.107 (0.099)	-0.025 (0.081)	0.019 (0.043)	0.023 (0.053)	0.039 (0.065)
3	mid-channel trough (m)	-0.091 (0.036)	0.148 (0.115)	0.123 (0.076)	0.135 (0.068)	0.122 (0.081)	0.124 (0.075)
4a	u/s depth variance (gini)	0.280 (0.109)	0.224 (0.066)	0.281 (0.060)	0.277 (0.055)	0.328 (0.063)	0.278 (0.071)
4b	d/s depth variance (gini)	0.283 (0.148)	0.253 (0.102)	0.300 (0.068)	0.275 (0.051)	0.309 (0.048)	0.284 (0.083)
5a	u/s thalweg gradient (m/m)	0.034 (0.025)	0.047 (0.062)	0.019 (0.024)	0.011 (0.027)	0.015 (0.015)	0.025 (0.031)
5b	d/s thalweg gradient (m/m)	0.004 (0.034)	0.026 (0.049)	0.020 (0.029)	0.014 (0.014)	0.019 (0.015)	0.017 (0.028)
6a	upstream pools (counts)	0.714 (0.958)	0.727 (0.750)	0.654 (0.676)	na	na	0.698 (0.795)
6b	downstream pools (counts)	0.643 (0.479)	0.545 (0.656)	0.577 (0.793)	na	na	0.588 (0.643)
7a	upstream pool depth (m)	0.209 (0.297)	0.277 (0.353)	0.213 (0.267)	na	na	0.233 (0.306)
7b	downstream pool depth (m)	0.314 (0.367)	0.260 (0.349)	0.183 (0.240)	na	na	0.252 (0.319)
8a	upstream LWD (counts)	0.786 (0.860)	0.682 (1.061)	2.519 (3.891)	3.000 (5.260)	1.765 (2.981)	1.75 (2.81)
8b	downstream LWD (counts)	1.286 (2.763)	0.864 (1.486)	3.074 (5.047)	3.042 (4.188)	2.412 (2.724)	2.14 (3.24)

The downstream gradients (Indictor 5b) in the 2013 dataset have a low average value; however, the coefficient of variation for the indicator is rather high. This reflects that half of this dataset, 7 out of 14, have a negative slope in the first year. This may be due to unconsolidated sediment that has not been formed into a low flow channel during construction.

Tables 3.5, 3.6, and 3.7 show the results of performance indicators 1 thru 8 for each cohorts 1, 2, and 3. For Cohort 1, we also compared the Year 2 and Year 5 data (Table 3.8). For all of the cohorts 1, 2, and 3 combined we compared Year 1 and Year 2 data (Table 3.9). Data were not collected for performance indicator 1 in Year 2013. Figures 3.10 through 3.13 show for cohorts 1, 2, and 3 the percent of culverts with changes of concern for different CoC thresholds. The percent of culverts with CoCs decreases as the CoC threshold increases.

For Cohort 1, between Years 1 and 2 (Table 3.5), the only statistically significant change was for Indicator 4a measuring changes in upstream depth variance through the Gini coefficient. The change in the Gini coefficient was negative; indicating that the upstream beds became flatter. The results of the randomization tests for contingency tables reveal that for some of the indicators the design type and the change of concern are not independent. These tests compare the influence that the culvert being either a no-slope or stream simulation design has on the changes of concern detected from the data. Culvert design type had a significant impact on the number of culverts with changes of concern for upstream thalweg gradient (5a), downstream thalweg gradient (5b), downstream pool frequency (6b), and downstream pool depth (7b). For all four indicators (5a, 5b, 6b, 7b), significantly more no-slope culverts than stream simulation culverts had changes of concern. Over half of the culverts in this dataset have thalweg gradient percent changes of greater than 20% (e.g., a slope increases from 5% to 6%). At first blush this may not seem to be a large increase, but if a 20% change in one direction occurs each consecutive year, a disconnect in geomorphic processes may develop.

Cohort 1 has the greatest percentage of CoCs for indicator 2b which measures upstream sediment bar development (Figure 3.10). It remains at 64% until the changes become greater than 40% indicating overall high percentages of change between the first and second year.

Between Years 1 and 2, Cohort 2 (Table 3.6) had statistically significant changes for mid-channel bar development (2a), downstream mid-channel trough development (3), and downstream depth variance (4b). Over 70% of culverts saw a decrease in elevation change for indicator 2a, and this percentage remains at over half of the cohort for decreases greater than or equal to 50% (Figure 3.11). This indicates that increases in mid-channel bar elevations occurred for a majority of the culverts in this cohort. Culvert design type had a significant impact on the number of culverts with changes of concern for upstream depth variance (4a), downstream depth variance (4b), and downstream thalweg gradient (5b). For each of these indicators, there were significantly fewer CoCs for stream simulation culverts than no-slope culverts. All of the culverts in this cohort meet the indicator 1 backwater criteria.

Cohort 3, between Years 1 and 2 (Table 3.7), consists of 27 total culverts – 19 stream simulation and 8 no-slope designs. Two culverts in this cohort fail to meet indicator 1 backwater criteria. There are statistically significant differences between years in mid-channel trough development (3), and downstream pool depth (7b), upstream large woody debris (LWD) and downstream LWD (8a and 8b). Similar to Cohort 2, a high percentage of significant change detected is through indicator 5b that indicates downstream gradients (Figures 3.11 and 3.12). This cohort did not have any no-slope culverts meet downstream gradient criteria at the highest change thresholds of 50%. This is a significant difference between design types. Additionally, nearly half have of this cohort has downstream decreases in large woody debris. The randomization test results determine the decrease in downstream LWD to be statistically significant. Twelve of the culverts have decreases in large woody debris in addition to increases in gradient. It is possible that the increases in stream power due to the gradient increases mobilized downstream large wood at these sites. The correlation matrices do not indicate statistically significant relationships between gradient and LWD, however (Table 3.12).

For Cohort 1, from Year 2 to Year 5 (Figure 3.13), the percentage of culverts that have CoCs decreases for all indicators and percent differences. The randomization test results show a statistically significant change between Year 2 and Year 5 for mid-channel bars (2a), mid-channel troughs (3), as well as upstream gradients (5a) (Table 3.8). For Cohort 1, for which we have 3 years of data, we plotted the values for the Gini coefficient and the channel gradient over time to display any trends (Figures 3.14 and 3.15). The Gini coefficients for these culvert cross-sections range from 0.13-0.56 upstream and 0.11-0.58 downstream. The upstream Gini coefficients in Year 1 have slightly less variance than then in Year 2 (Table 3.10, Figure 3.14), however, by Year 5 the variance decreases to below Year 1 levels as shown by the standard deviations around the mean. Several culverts in Cohort 1 have increased downstream Gini coefficient values by Year 5 as well.

Immediately after construction (Year 1), upstream channel slopes in Cohort 1 ranged from 0.00 to 0.03 m/m (Figure 3.15). By Year 2, there was no discernable pattern in how channel slopes upstream of the culvert changed over time. Some slopes increased, some decreased, and some stayed about the same. Two culverts went from a non-negative slope to negative slope upstream of the culverts; however, by Year 5 the culverts level off or decrease in gradient. A different trend appears among the downstream gradients. Immediately after construction (Year 1), downstream channel slopes ranged from -0.06 to 0.06 m/m. Between years 1 and 2 negative slopes tended to increase and positive slopes tended to decrease. By Year 5, the downstream gradients appear to be more similar to their original gradients post-construction.

It is also important to acknowledge that local changes and variation in gradient within the vicinity of the culvert may function differently than average slope across the reach scale. We do not expect the slopes across greater longitudinal lengths to change as readily as those that are more directly influenced by project construction as well as the road crossing itself. This is in line with the dynamic equilibrium concept where local changes that occur will cause local and sometimes large shifts in slope whereas the average slope of the channel through time changes slowly at a gradual rate from long-term fluvial incision.

The longitudinal profiles measured in subsequent years will allow for comparisons between slopes measured between cross-sections, and reach-scale slopes measured over 30 bankfull widths (*sensu* Harrelson et al. 1994). However, for the culvert to be considered effective through time, the ratio of gradient change between the culvert cross-sections and the greater reach will be monitored to ensure that the slope of the culvert does not create a disconnection in the channel. These disconnections are common among culverts that are not installed at the correct slope.

Correlations Among Indicators

The correlation matrices for all of the culverts in Cohorts 1-3 indicate statistically significant relationships between indicators (Table 3.11). There are more statistically significant relationships in the number and depth of pools with large woody debris in the Year 1 post-construction data than in Year 2. One of the two relationships that occur in both years is between upstream and downstream large wood counts. The second relationship that persists is between upstream mid-channel bar formation and downstream troughs.

Table 3.5. Results of performance indicators 1 through 8 for comparison of culverts in year 1 and year 2 for the 2013 cohort (Cohort 1). The table indicates the mean changes that correspond to each of the indicators, along with the design type of each of the culverts with a change of concern (CoC). For indicators 2a through 5b, dashes between numbers (e.g., 3-4) denote the number of CoCs for CoC thresholds of 10% and 50%. The table also provides the mean change between the two years (Year 2- Year 1) given in the units of each indicator for all of the sites combined as well as for each design type. Negative numbers indicate a decrease in values through time. For example, Indicator 6b reveals a decrease in the number of downstream pools. Asterisks denote significance at the $p \leq 0.05$** and $0.05 < p \leq 0.10$* levels.

Indicator	**Description (units)**	**Number of Culverts**	**Mean Change**	**Std. Dev. of Mean Change**	**Design Type with Change of Concern**		**Mean Difference Change by Culvert Type**	
					Stream Simulation (8 total)	No-slope (6 total)	Stream Simulation (8 total)	No-slope (6 total)
1	year 2 backwater	na	na	na	0	0	na	na
2a	mid-channel bar (m)	14	-0.027	0.042	5-5	3-5	-0.011	-0.050
2b	mid-channel bar (m)	14	-0.002	0.015	3-4	5-5	0.025	-0.038
3	mid-channel trough (m)	14	0.180	0.006	2-4	1-2	0.008	0.008
4a	u/s depth variance (gini)	14	-0.019**	0.077	0-2	0-0	-0.013	-0.028
4b	d/s depth variance (gini)	14	-0.007	0.108	3-4	2-5	-0.038	0.034
5a	u/s thalweg gradient (m/m)	14	-0.004	0.036	0-2	4**-4	0.001	-0.011
5b	d/s thalweg gradient (m/m)	14	0.007	0.030	1-3	4**-4	0.008	0.007
6a	upstream pools (counts)	14	0.000	1.176	2	2	0.500	-0.667
6b	downstream pools (counts)	14	-0.214	0.700	1	4**	-0.250	-1.667
7a	upstream pool depth (m)	14	-0.028	0.207	1	4	0.026	-0.100
7b	downstream pool depth (m)	14	-0.038	0.290	2	5**	0.016	-0.111
8a	upstream LWD (counts)	14	-0.286	0.914	3	0	-0.250	-0.333
8b	downstream LWD (counts)	14	-0.714	2.998	2	1	-1.500	0.333

Table 3.6. Results of performance indicators 1 through 8 for comparison of culverts in year 1 and year 2 for the 2014 cohort (Cohort 2). The table indicates the mean changes that correspond to each of the indicators, along with the design type of each of the culverts with a change of concern (CoC). For indicators 2a through 5b, dashes between numbers (e.g., 3-4) denote the number of CoCs for CoC thresholds of 10% and 50%. The table also provides the mean change between the two years (Year 2 - Year 1) given in the units of each indicator for all of the sites combined as well as for each design type: stream simulation or no-slope. Negative numbers indicate an increase in values through time. For example, Indicator 7b reveals a decrease in the downstream pool depth. Asterisks denote significance at the $p \leq 0.05$** and $0.05 < p \leq 0.10$* levels.

Indicator	**Description (units)**	**Number of Culverts**	**Mean Change**	**Std. Dev. of Mean Change**	**Design Type with Change of Concern**		**Mean Difference Change by Culvert Type**	
					Stream Simulation (16 total)	No-slope (6 total)	Stream Simulation (16 total)	No-slope (6 total)
1	year 2 backwater	14	-	-	0	0	-	-
2a	mid-channel bar (m)	22	-0.096**	0.026	8-11	4-4	-0.078	-0.143
2b	mid-channel bar (m)	22	0.013	0.028	3-6	0-1	0.006	0.032
3	mid-channel trough (m)	22	-0.032**	0.037	2-3	1-2	-0.078	-0.070
4a	u/s depth variance (gini)	22	-0.011	0.049	0-6	0**-4	-0.012	-0.006
4b	d/s depth variance (gini)	22	-0.032**	0.067	0-0	0-2**	-0.038	0.006
5a	u/s thalweg gradient (m/m)	22	-0.016	0.035	5-9	1-2	-0.018	0.002
5b	d/s thalweg gradient (m/m)	22	0.002	0.013	4-6	4*-4	0.000	0.010
6a	upstream pools (counts)	22	0.100	0.911	3	2	0.200	-0.200
6b	downstream pools (counts)	22	0.050	0.759	7	4	0.200	-0.400
7a	upstream pool depth (m)	22	0.255	1.692	2	2	-0.041	1.140
7b	downstream pool depth (m)	22	-0.077	0.198	6	3	-0.019	-0.250
8a	upstream LWD (counts)	22	0.400	0.821	1	0	0.533	0.000
8b	downstream LWD (counts)	22	0.200	1.436	2	1	0.333	-0.200

Table 3.7. Results of performance indicators 1 through 8 for comparison of culverts in year 1 and year 2 for the 2015 cohort (Cohort 3). The table indicates the number and percent of changes of concern detected at each site, along with the design type of each of the culverts with a change of concern (CoC). For indicators 2a through 5b, dashes between numbers (e.g., 3-4) denote the number of CoCs for CoC thresholds of 10% and 50%. The table also provides the mean change between the two years (Year 2 - Year 1) given in the units of each indicator for all of the sites combined as well as for each design type: stream simulation or no-slope. Negative numbers indicate a decrease in values through time. For example, Indicator 7b reveals a decrease in the downstream pool depth. Asterisks denote significance at the $p \leq 0.05$** and $0.05 < p \leq 0.10$* levels.

Indicator	**Description (units)**	**Number of Culverts**	**Mean Change**	**Std. Dev. of Mean Change**	**Design Type with Change of Concern**		**Mean Difference Change by Culvert Type**	
					Stream Simulation (19 total)	No-slope (8 total)	Stream Simulation (19 total)	No-slope (8 total)
1	year 2 backwater	15	-	-	2	-	-	-
2a	mid-channel bar (m)	27	0.008	0.004	4-8	0-1	0.151	0.029
2b	mid-channel bar (m)	27	-0.013	0.006	7-8	1-2	-0.078	-0.004
3	mid-channel trough (m)	27	-0.030**	0.030	2-4	1-3	-0.027	-0.031
4a	u/s depth variance (gini)	27	0.008	0.063	0-5	0-2	0.007	-4.67E-05
4b	d/s depth variance (gini)	27	-0.030	0.100	0-3	1-3	-0.021	-0.043
5a	u/s thalweg gradient (m/m)	27	0.007	0.022	3-4	2-3	0.008	-0.005
5b	d/s thalweg gradient (m/m)	27	0.004	0.019	7-7	3-8**	0.003	0.010
6a	upstream pools (counts)	27	0.0	0.480	1	2	0.052	-0.125
6b	downstream pools (counts)	27	-0.1	0.698	3	0	-0.211	0.125
7a	upstream pool depth (m)	27	0.021	0.155	5	5*	0.028	0.005
7b	downstream pool depth (m)	27	-0.061**	0.172	5	3	-0.074	-0.033
8a	upstream LWD (counts)	27	-1.0*	2.732	8	3	-1.158	-0.625
8b	downstream LWD (counts)	27	-1.3*	2.353	11	2	-1.684	-0.500

Table 3.8. Results of culvert performance indicators 1 through 8 for comparison of culverts in year 2 and year 5 for the 2013 cohort (Cohort 1). The table indicates the mean changes that correspond to each of the indicators, along with the design type of each of the culverts with a change of concern (CoC). For indicators 2a through 5b, dashes between numbers (e.g., 3-4) denote the number of CoCs for CoC thresholds of 10% and 50%. The table also provides the mean change between the two years (Year 5- Year 2) given in the units of each indicator for all of the sites combined as well as for each design type: stream simulation or no-slope. Negative numbers indicate a decrease in values through time. For example, Indicator 8b reveals a decrease in the amount of downstream large woody debris. Asterisks denote significance at the $p \leq 0.05$** and $0.5 < p \leq 0.10$* levels.

Indicator	**Description (units)**	**Number of Culverts**	**Mean Change**	**Std. Dev. of Mean Change**	**Design Type with Change of Concern**		**Mean Difference Change by Culvert Type**	
					Stream Simulation (6 total)	No-slope (5 total)	Stream Simulation (6 total)	No-slope (5 total)
1	year 2 backwater	na	na	na	0	0	na	na
2a	mid-channel bar (m)	11	-0.037**	0.050	1-1	3-3	-0.049	-0.079
2b	mid-channel bar (m)	11	0.017	0.001	2-2	0-1	-0.013	0.041
3	mid-channel trough (m)	11	-0.003**	0.000	1-1	1-1	0.034	0.012
4a	u/s depth variance (gini)	11	0.003	0.082	1-2	2	0.023	-0.020
4b	d/s depth variance (gini)	11	0.010	0.126	2-3	2	-0.006	0.028
5a	u/s thalweg gradient (m/m)	11	-0.013**	0.035	1-4	3-4	-0.012	-0.014
5b	d/s thalweg gradient (m/m)	11	0.011	0.021	2-4	2-3	0.018	0.002
6a	upstream pools (counts)	11	0.272	1.272	1	1	-0.500	1.200
6b	downstream pools (counts)	11	0.272	0.647	2	0	0.167	0.400
7a	upstream pool depth (m)	11	0.080	0.176	0	0	0.030	0.140
7b	downstream pool depth (m)	11	-0.066	0.236	2	2	-0.067	-0.065
8a	upstream LWD (counts)	11	0.091	0.302	0	0	0.167	0.000
8b	downstream LWD (counts)	11	-0.091	0.302	1	0	0.000	-0.200

Table 3.9. Results of culvert performance indicators 1 through 8 for all of the culverts in Cohorts 1-3. The table indicates the number and percent of changes of concern detected at each site, along with the design type of each of the culverts with a change of concern (CoC). For indicators 2a through 5b, dashes between numbers (e.g., 3-4) denote the number of CoCs for CoC thresholds of 10% and 50%. The table also provides the mean change between two years (Year 2- Year 1) given in the units of each indicator for all of the sites combined as well as for each design type: stream simulation or no-slope. Negative numbers indicate a decrease in values through time. For example, Indicator 8b reveals a decrease in the amount of downstream large woody debris.

Indicator	Description (units)	Number of Culverts	Mean Change	Std. Dev. of Mean Change	Design Type with Change of Concern		Mean Difference Change by Culvert Type	
					Stream Simulation (43 total)	No-slope (20 total)	Stream Simulation (43 total)	No-slope (20 total)
1	year 2 backwater	29	na	na	2	0	na	na
2a	mid-channel bar (m)	63	-0.039	0.122	15-23	6-8	0.021	-0.055
2b	mid-channel bar (m)	63	-0.0002	0.070	12-19	6-8	-0.015	0.003
3	mid-channel trough (m)	63	-0.023	0.067	6-12	3-7	-0.015	-0.036
4a	u/s depth variance (gini)	63	-0.006	0.061	0-12	2-6	-0.006	-0.011
4b	d/s depth variance (gini)	63	-0.022	0.090	2-7	3-9	-0.032	-0.001
5a	u/s thalweg gradient (m/m)	63	0.002	0.023	8-15	10-12	0.003	-0.002
5b	d/s thalweg gradient (m/m)	63	0.005	0.020	12-16	12-16	0.004	0.008
6a	upstream pools (counts)	63	0.033	0.809	6	6	0.251	-0.331
6b	downstream pools (counts)	63	-0.082	0.708	11	8	-0.087	-0.147
7a	upstream pool depth (m)	63	0.087	0.962	8	11	0.005	0.348
7b	downstream pool depth (m)	63	-0.061	0.207	13	11	-0.025	-0.131
8a	upstream LWD (counts)	63	-0.377	1.985	12	3	-0.292	-0.319
8b	downstream LWD (counts)	63	-0.689	2.316	15	4	-0.950	-0.122

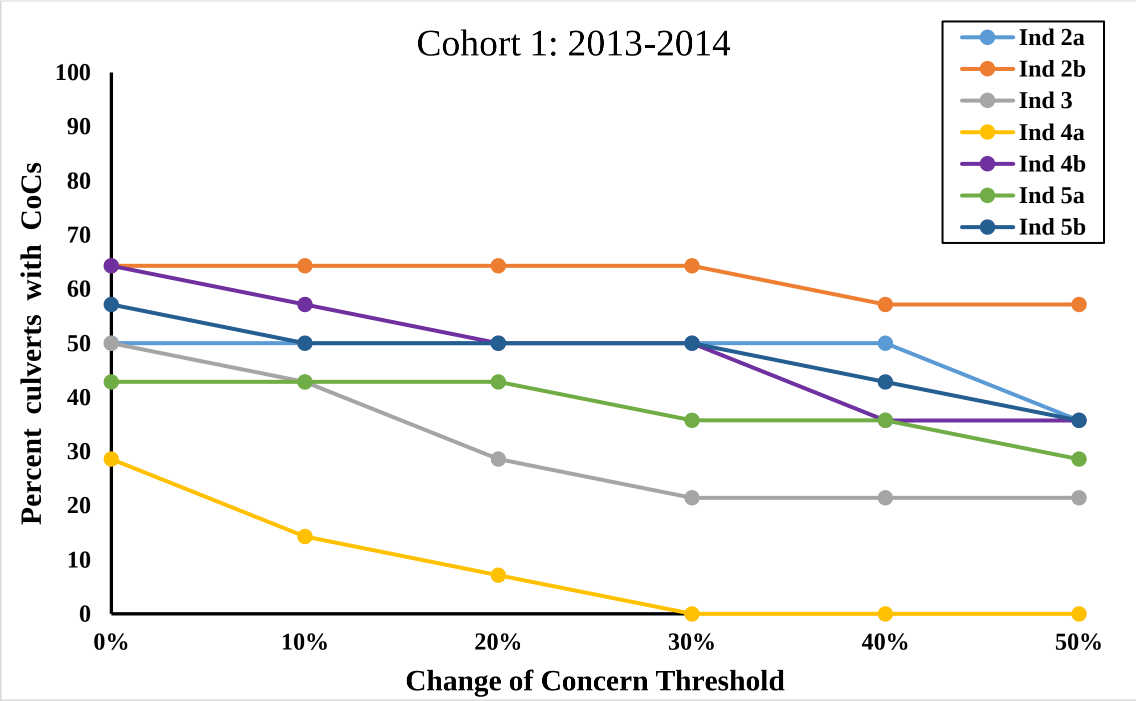

Figure 3.10. Cohort 1 data (Years 1 and 2) showing the percentage of culverts considered to have a change of concern (CoC) based on the percent difference of each indicator between the two years (n=14).

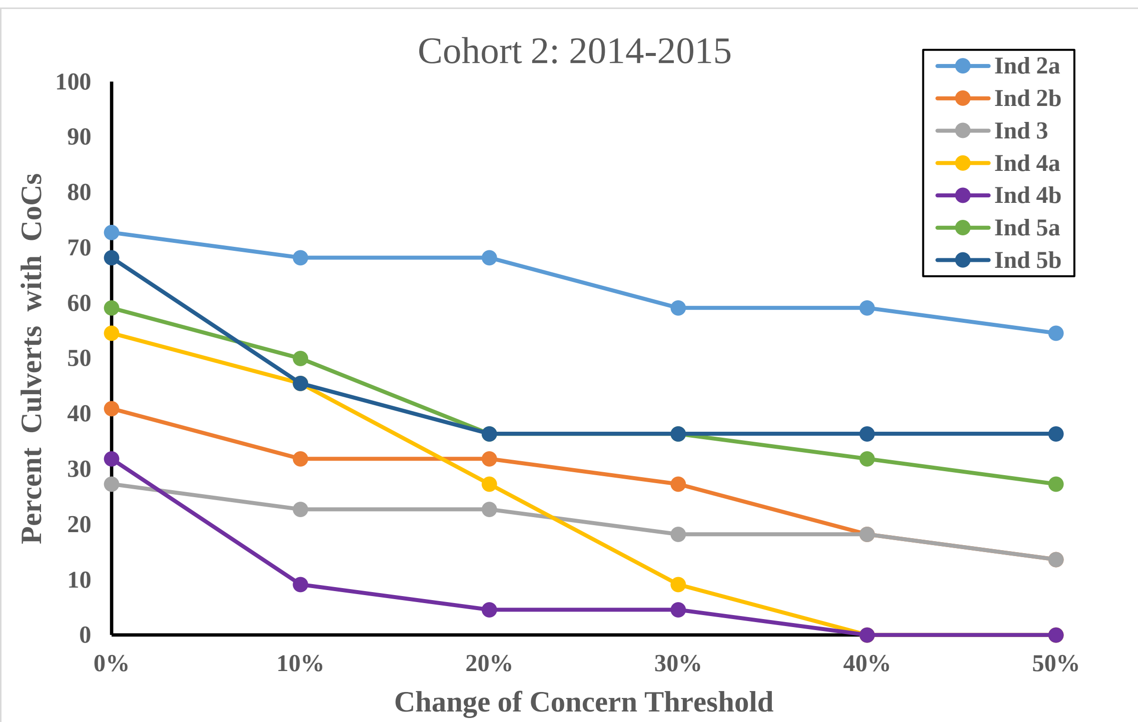

Figure 3.11. Cohort 2 data (Years 1 and 2) showing the percentage of culverts considered a have a change of concern (CoC) based on the percent difference of each indicator between the two years (n=22).

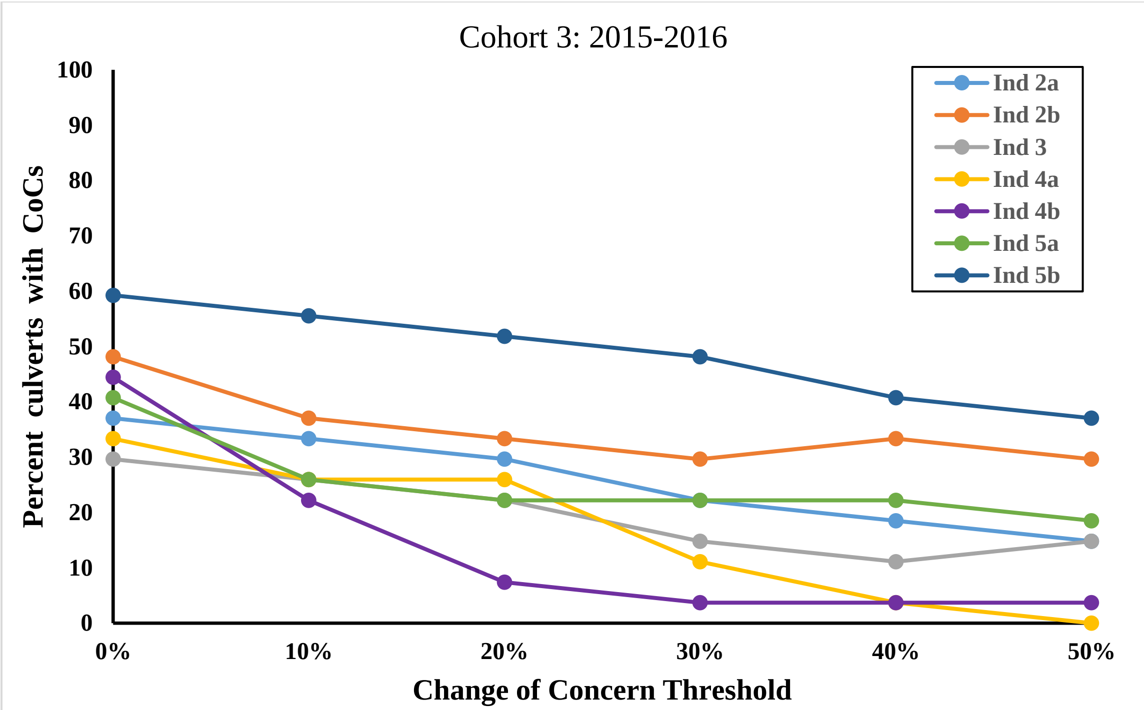

Figure 3.12. Cohort 3 data (Years 1 and 2) showing the percentage of culverts considered to have a change of concern (CoC) based on the percent difference of each indicator between the two years (n=27).

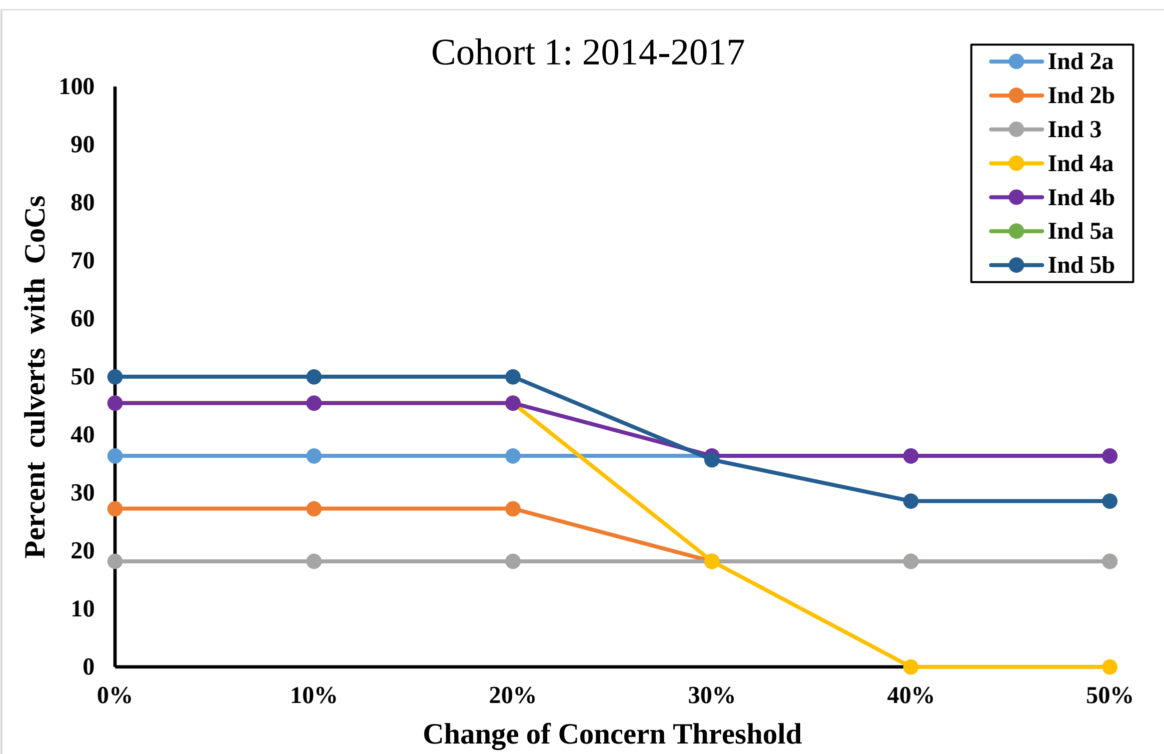

Figure 3.13. Cohort 1 data (Years 2 and 5) showing the percentage of culverts considered to have a change of concern (CoC) based on the percent difference of each indicator between the two years (n=11).

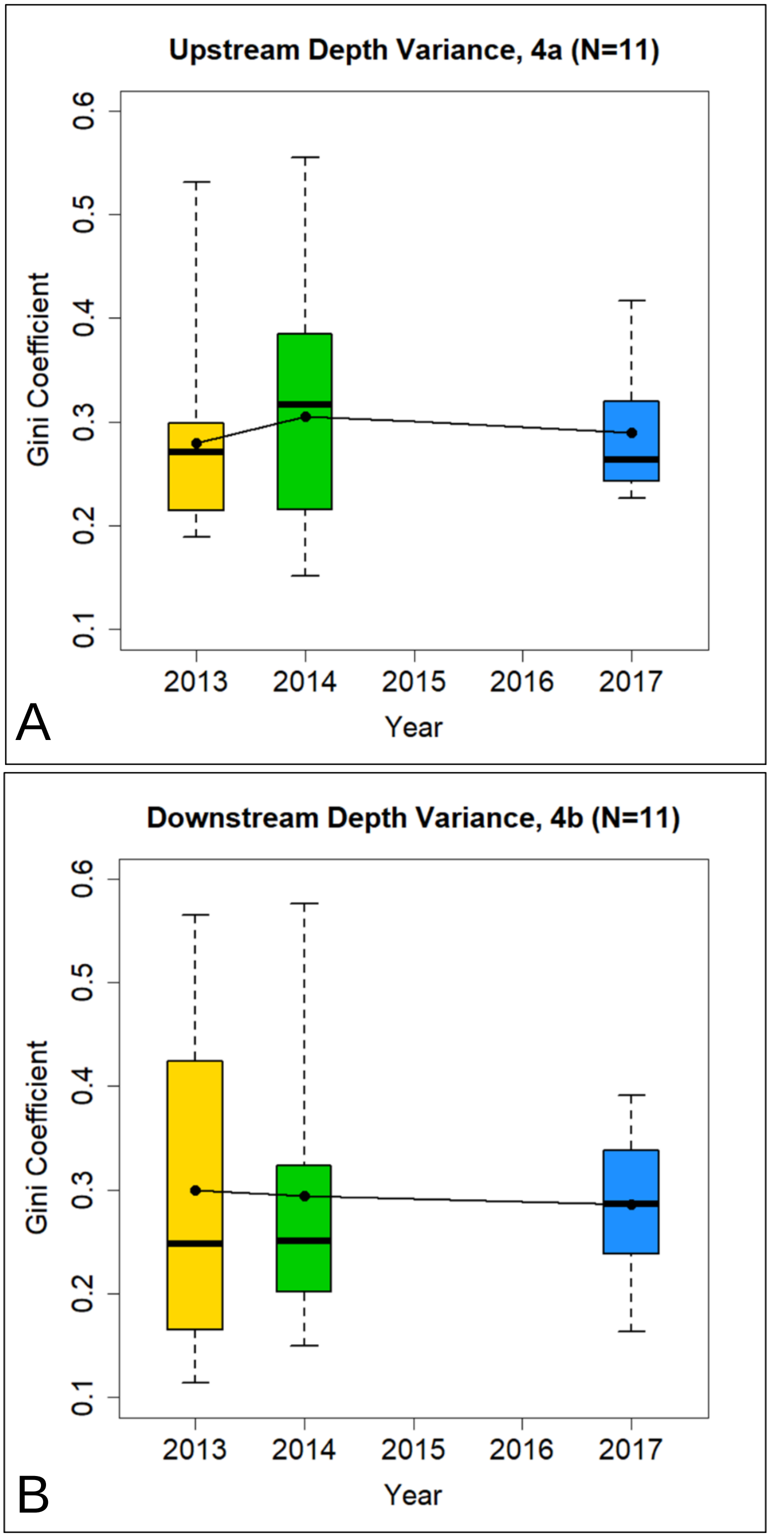

Figure 3.14. Cohort 1 data for A) upstream and B) downstream depth variance as characterized by the Gini Coefficient. An increase in the Gini Coefficient represents an increase in channel cross-section variance and complexity. Downstream of culvert, an increase in the Gini Coefficient may also indicate deepening of the channel. Thick black line within box is median, ends of box are inter-quartile range, ends of whiskers are full range of data, small black dot is the mean.

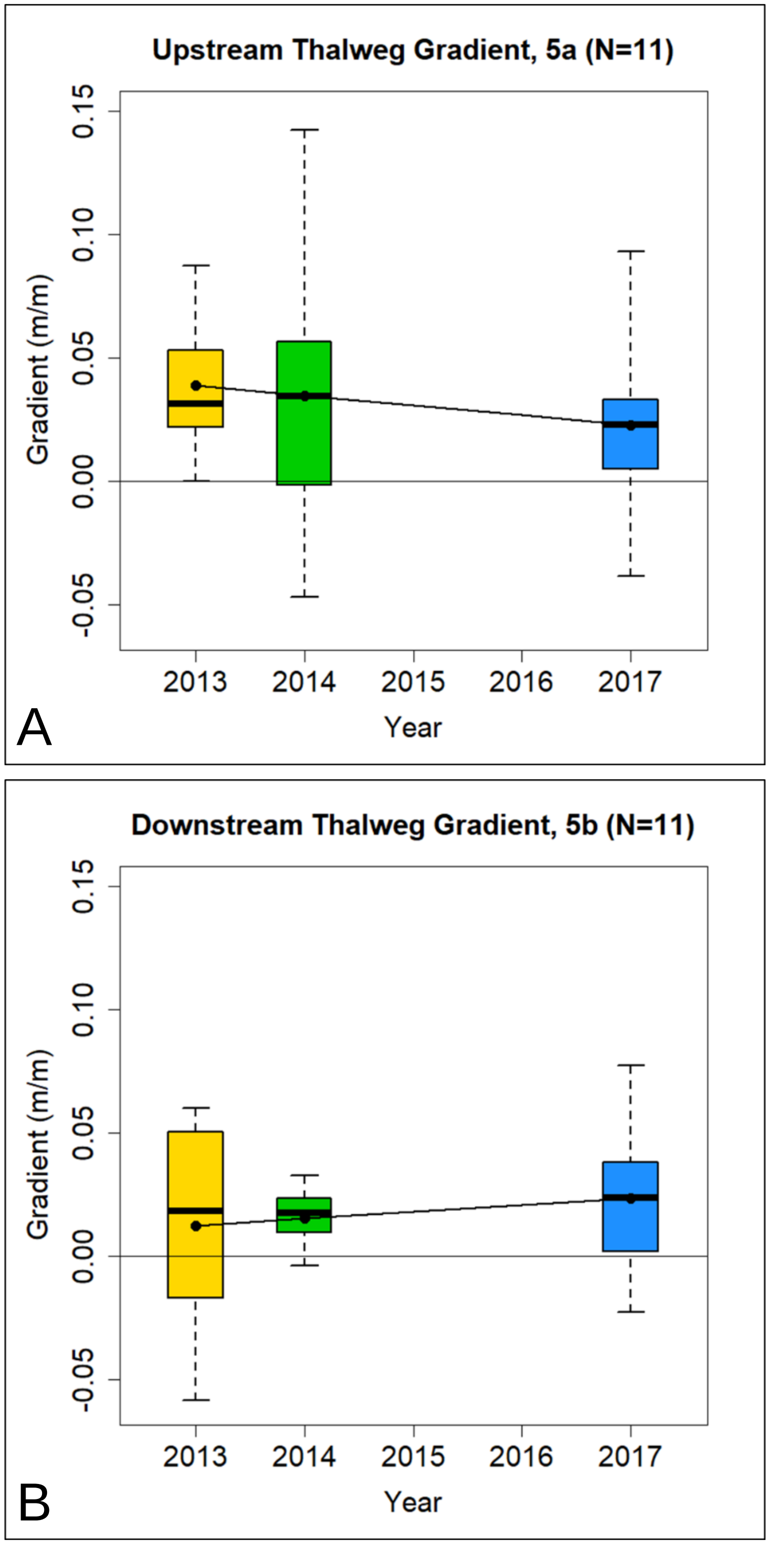

Figure 3.15. Cohort 1 data for A) upstream and B) downstream gradient. An increase in the gradient represents a steepening of the channel. Thick black line within box is median, ends of box are inter-quartile range, ends of whiskers are full range of data, small black dot is the mean.

Table 3.10. Statistics of the upstream and downstream Gini coefficients and channel gradients for years 1, 2, and 5 for Cohort 1.

		Gini coefficient		Channel Gradient	
Year	**Statistic**	**Upstream**	**Downstream**	**Upstream**	**Downstream**
2013	Avg.	0.28	0.28	0.034	0.004
	Std. dev.	0.11	0.15	0.025	0.034
2014	Avg.	0.32	0.30	0.031	0.011
	Std. dev.	0.12	0.12	0.052	0.011
2017	Avg.	0.30	0.29	0.022	0.024
	Std. dev.	0.07	0.07	0.033	0.028

Table 3.11. Correlation matrices for Cohorts 1-3 indicators. The cells contain the correlation coefficients for all of the indicators. Relationships significant at the 0.05 level have orange cells, and the relationships significant at the 0.10 level have light orange cells. The heavy black borders identify relationships that are significant in both Year 1 and Year 2.

Cohorts 1-3 Combined – Year 1

	2a	2b	3	4a	4b	5a	5b	6a	6b	7a	7b	8a	8b
2a	1												
2b	0.19	1											
3	0.13	-0.36	1										
4a	-0.1	0.16	0.07	1									
4b	0.22	0	0.02	0.13	1								
5a	0.15	-0.18	0.21	-0.03	0.1	1							
5b	0.05	-0.12	0.11	0.01	-0.03	0.45	1						
6a	-0.22	-0.17	-0.12	-0.15	-0.1	-0.16	-0.1	1					
6b	-0.15	-0.19	0.13	0.07	-0.07	0.15	0.18	0.21	1				
7a	-0.28	-0.31	-0.08	-0.18	0.02	-0.14	-0.06	0.59	0.4	1			
7b	-0.16	-0.38	-0.01	-0.06	0	0.15	0.18	0.17	0.65	0.52	1		
8a	-0.37	-0.02	-0.1	0	-0.1	-0.2	-0.12	0.16	0.05	0.17	0.07	1	
8b	-0.19	0.07	0.12	0.18	0.15	0.05	-0.03	-0.18	0.38	-0.01	0.11	0.29	1

Cohorts 1-3 Combined – Year 2

	2a	2b	3	4a	4b	5a	5b	6a	6b	7a	7b	8a	8b
2a	1												
2b	0.45	1											
3	0.07	-0.37	1										
4a	0.25	0.22	-0.25	1									
4b	-0.01	0	-0.16	0.27	1								
5a	-0.05	-0.06	0.13	-0.11	-0.02	1							
5b	0.01	-0.06	0.15	0.05	0.12	0.33	1						
6a	0	0.08	-0.18	-0.03	0.11	-0.13	-0.15	1					
6b	-0.26	-0.29	0.07	0	-0.13	0.12	-0.2	0.01	1				
7a	0.09	0.19	0.03	0.12	0.1	-0.01	-0.1	0.14	-0.13	1			
7b	-0.39	-0.19	-0.19	-0.01	0.03	0.16	-0.02	-0.02	0.53	-0.06	1		
8a	-0.13	-0.16	0.11	-0.07	0.02	-0.16	-0.01	0.19	-0.1	-0.03	-0.12	1	
8b	-0.24	-0.03	0.02	-0.05	-0.03	0.21	-0.03	-0.05	-0.03	-0.06	0.06	0.21	1

Substrate Comparisons

Most culverts exhibited no consistent change in substrate (Table 3.12). Percent of transect stations exhibiting coarsening or fining are comparable, indicating that, over the first year substrate size did not substantially change. This trend continues with the Year 5 data. Sediment data for Cohort 1 (Figure 3.12), and do not see a discernible trend among the 11 culverts. For Cohort 1, mean substrate sizes across all three years and all culverts was approximately fine (size class 3) to coarse gravel (size class 4), that is, mean category numbers stayed between 2.5 and 4.5.

The changes in sediment through the culvert structure itself show a range of changes at each site, from 0% to 52% for all three cohorts (Table 3.13). We derived these percentages from the associated numeric code to reflect changes in sediment category. For Cohort 1, the greatest increase in substrate size is 43%. This culvert has on average increased in sediment size by almost one category. In Cohort 2, the greatest increase is 52%, and in this culvert sediment has increased in size from fines (size class 1) to fine gravel (size class 3). Cohort 3 had the largest number of longitudinal transects through the culvert. Of those 13 transects, bed sediments become finer along 4 and became coarser along 8 over the first year. However, looking at all three cohorts, there is almost an equal proportion of culverts in which bed sediments have coarsened or have become finer over the first year.

Table 3.12. Comparisons between years of sediment size class at culvert cross sections. Values are mean percent of stations per cross section at which sediments became coarser, finer, or did not change. Cross section location is relative to culvert.

				Mean Percent of Stations per Cross Section		
Cohort	**Cohort Years**	**Number of culverts**	**Cross Section Location**	**Coarser**	**Finer**	**No Change**
1	2013 & 2014	14	Upstream	29	24	46
			Downstream	29	28	43
			All	29	26	45
2	2014 & 2015	22	Upstream	35	27	38
			Downstream	26	28	45
			All	31	28	41
3	2015 & 2016	27	Upstream	21	38	40
			Downstream	27	26	44
			All	26	31	42
1, 2, 3	1 year of change	63	Upstream	28	30	41
			Downstream	27	27	44
			All	28	28	43
1	2014 & 2017	11	Upstream	35	38	40
			Downstream	27	26	44
			All	33	27	38

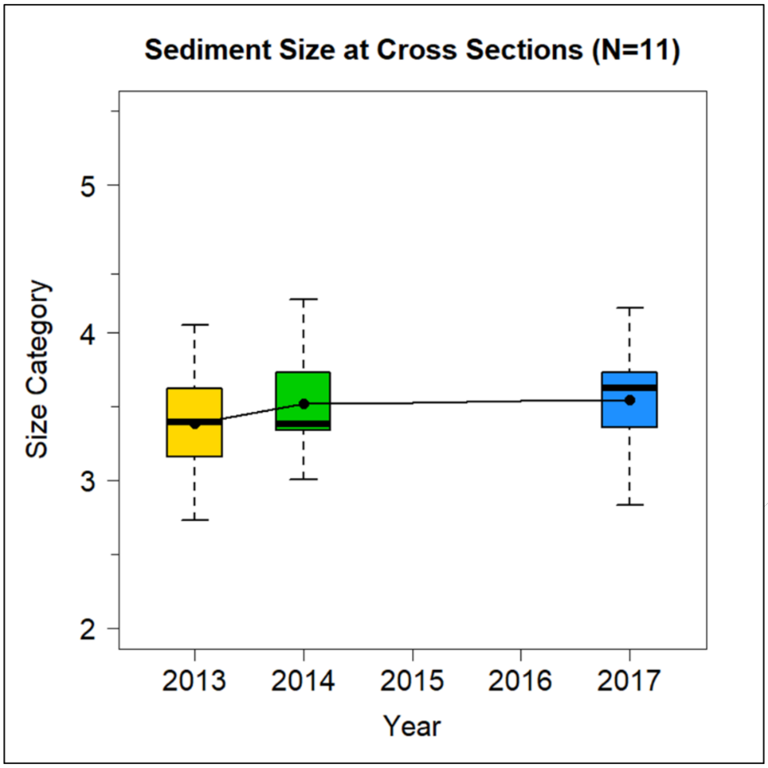

Figure 3.16. Cohort 1 mean sediment sizes at channel cross sections for years 2014 through 2017. Vertical axis is sediment size categories with smaller numbers equated to smaller sediment sizes (see Table 3.2). Thick black line within box is median, ends of box are inter-quartile range, ends of whiskers are full range of data, small black dot is the mean.

Table 3.13. Within-culvert (i.e., longitudinal transect) substrate comparisons for each cohort. Shown below are the percent differences in substrate size category for each culvert. A negative sign indicates that the substrate became finer. The numbers in bold indicate the lowest and highest percent change for each cohort.

Cohort 1			**Cohort 2**		**Cohort 3**	
culvert id	percent difference 2013-2014	percent difference 2014-2017	culvert id	percent difference 2014-2015	culvert id	percent difference 2015-2016
1-1	**1**	5	2-1	**52**	3-1	**0**
1-2	6	5	2-2	-3	3-2	2
1-3	22	-6	2-3	-1	3-3	16
1-4	8	4	2-4	**1**	3-4	-21
1-5	15	-2	2-5	-5	3-5	-3
1-6	8	**0**	2-6	3	3-6	4
1-7	**43**	**22**	2-7	-3	3-7	-7
			2-8	-16	3-8	4
					3-9	-6
					3-10	23
					3-11	4
					3-12	1
					3-13	**32**

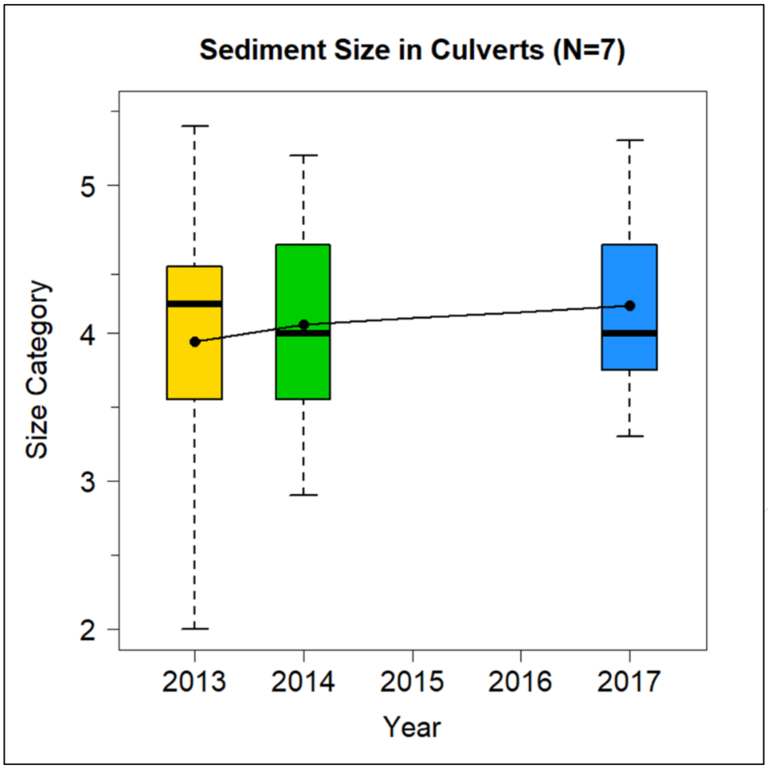

Figure 3.17. Cohort 1 mean sediment size along longitudinal transect within culvert from years 2014 through 2017. Vertical axis is sediment size categories with smaller numbers equated to smaller sediment sizes (see Table 3.2). Thick black line within box is median, ends of box are inter-quartile range, ends of whiskers are full range of data, small black dot is the mean.

Discussion

To test the hypothesis that newly constructed culverts compliant with Hydraulic Code Rules effectively maintain geomorphic processes, we must monitor them over multiple years. Over the first 4 years of effectiveness monitoring, culverts were visited at years 1 (immediately after construction), 2, and 5. We had expected channels near and through new culverts to adjust considerably during the first year post-construction, and approach an equilibrium condition during that time. Channels did adjust between years 1 and 2, however, we found channel form continued to adjust between years 2 and 5. Hence, for the sake of cost-efficiency, we believe year-2 visits add little useful information with which to judge long-term effectiveness of culverts. While it was interesting to see how culverts change at the beginning of their service life, we now believe that Year 2 measurements are unnecessary, and as of 2017 we no longer visit culverts at Year 2. We now believe collecting data in Year 5 makes more sense because the streambed will have had time to adjust to a variety of flow events. While this runs the risk of not identifying performance failures that occur before Year 5, that risk is low for culverts that were implemented correctly according to fish passage design guidelines. Cohort 1, which has data for years 1, 2, and 5, supports the hypothesis that after several years of undergoing fluvial processes, culvert stream beds will stabilize, with fewer changes of concern based on performance indicators. For example, the percent of culverts with gradient decreases downstream is lower than the other cohorts as well as the same cohort when comparing years 1 and 2. However, more years of data are needed to determine whether performance indicators have stabilized or are fluctuating.

One shortcoming of the initial effectiveness monitoring protocols is that the stream data has been collected only in the vicinity of the culvert. We have revised the data collection to include a longitudinal profile (Figure 3.6) that better captures changes that may be occurring at the reach scale. The intent here is to capture culvert impacts that may be happening further upstream or downstream, and to track the morphological changes of the greater stream reach. This will provide evidence of culvert effectiveness by comparing indicators such as gradient, pool depths, etc., both in reference sites outside of the culvert influence, as well as near the culvert, to determine if it is in fact simulating the stream. The trade-off to save time has been to reduce the number of elevations taken along each cross-section. This requires additional training and expertise from the field technicians to recognize the appropriate number of elevations to take depending on channel complexity rather than a pre-determined set number. We will begin reach-scale analysis as more Year 5 data is collected to maximize efficiencies by ensuring that we are capturing the stream after enough seasonal flows have occurred to stabilize the culverts after implementation.

The current data collection will continue to inform future analyses to help determine the effectiveness of our current design guidelines and hydraulic code rules. At present, we have no strict definition of culvert effectiveness. Hence, we developed "performance indicators" with which to gauge the effectiveness of our current culvert designs. Our indicators were based on professional knowledge of problems commonly associated with undersized culverts. The performance indicators are the most critical parameters currently identified for culvert performance, although we will continue to refine analyses to make determinations regarding culvert effectiveness as we learn more. For example, the results show which culverts have significant change associated with them for each indicator, but we have not made any determinations of how these tests and associated parameters should potentially be weighted to reflect their relative importance. Further investigation into these problems may also lead to better understanding of the influences that design type has on culvert performance.

We do not interpret the changes that occurred over the first year post-construction as indications of culvert success or failure at simulating the stream. However, they do provide us with indicators to monitor in future years for potential stream degradation through time. Through more analysis of culverts that have been installed for a number of years, we can develop more rigorous criteria to better assess overall performance. It is clear based on the initial results provided here that it will require 5 years of data before we can determine if a culvert is performing as intended based on its fluvial form and process indicators. If, after this amount of time, we see culverts continuing to have large percent changes based on the indicators, then we can follow up with in-depth investigation of why this is the case. The effectiveness monitoring program will also continue to track general trends and areas where we may improve guidelines such as in culvert channel bed design.

Conclusions

Culverts that have been properly implemented according to their permit since 2013 have been included in the effectiveness monitoring project. There are currently five cohorts with year-one monitoring, three of those cohorts have two years of data, and one cohort has Year 5 data collected in 2017. In the first year after installation, all culvert pass Level A assessments despite the fact that many of the culverts have undergone changes in channel bed variability and gradient. Changes of concern include reductions in the large wood, as well as the number and size of pools in the culvert reaches. We believe for now that these changes are likely due to the stream readjustments post-construction, and are not indicative of culvert effectiveness. This is supported by the Year 5 data that demonstrates an overall decrease in the amount of changes of concern detected at these sites. The upcoming Year 5 data collection will be an important contribution to further test this belief.

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Part 4. Implementation Monitoring of Marine Shoreline Armoring

Introduction

Washington's marine shorelines are an important ecological, cultural and economic resource. Complex geomorphic processes have shaped, and continue to shape, coastal shorelines through continual erosion and deposition of sediments. The erosion of adjacent uplands, in particular, has raised .concerns about the maintenance or restoration of natural sediment movement, which build beaches versus the armoring of shorelines to protect coastal properties from erosion (Shipman et al. 2010). Shoreline armor, in the form of hard vertical barriers such as bulkheads, seawalls, and revetments, is one of the most significant human impacts to shorelines of Puget Sound. These structures are intended to prevent shoreline erosion, reduce coastal flooding, and protect upland development (e.g., roads, railways, homes, and agriculture). Currently, nearly a third of Puget Sound's shorelines have been armored, with the greatest concentration of armoring on the eastern shore of central Puget Sound within King and Pierce counties (MacLennan et al. 2017).

Issues surrounding marine shoreline armor are complex and often controversial, as the actual risks to coastal properties and impacts of armoring to shoreline environments are not fully understood. Shoreline armor is intended to stop or reduce wave-induced coastal erosion. However, hard armoring has been shown to have both direct and indirect impacts on ecological structure and function including, but not limited to: a) decrease in intertidal habitat structure, such as riparian vegetation and log accumulation (Dethier et al. 2016); b) modification or loss of forage fish habitat (Penttila 2007); c) alteration of beach sediment dynamics (Shipman et al. 2010); and d) disruption of terrestrial and marine nutrient exchange (Heerhartz et al. 2014). Furthermore, armor-induced impacts to beach environments occur across a range of local to broader scales and may not be detected for years to decades or until cumulative thresholds are exceeded (Dethier et al. 2016).

The Washington Department of Fish and Wildlife (WDFW) has responsibility and authority to protect nearshore habitat while recognizing private property rights. Under the state Hydraulic Code, WDFW regulates the design and construction of shoreline structures at or below the ordinary high water mark (OWHM)[32] to avoid "permanent loss of critical food fish habitat."[33] Hydraulic Project Approval (HPA) permits stipulate protective provisions for shoreline armor that ensure: (a) the waterward face of a new bulkhead is located at or above the OHWM, but where this is not feasible a bulkhead may extend no more than six feet waterward of the OHWM; and (b) the waterward face of a replacement or repaired bulkhead is located no farther waterward than the structure it is replacing, however, under certain circumstances, the replacement bulkhead may extend waterward of, but directly abutting, the existing structure, and the bulkhead design must use the least-impacting type of structure (WAC 220-660-370).[34]

The success of the HPA process to implement state rules to protect nearshore habitats and marine waterfront property relies on 1) WDFW's issuance of high quality HPA permits, and 2) permittees' compliance with their permits. To evaluate the performance of both permittor and permittee, and improve the overall success of the HPA process, WDFW is monitoring the implementation of HPA permits and

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[32] Ordinary high water mark - where the presence and action of waters are so common and usual, and so long continued in all ordinary years, as to mark upon the soil a character distinct from that of the abutting upland, in respect to vegetation (Anderson et al. 2016).

[33] WDFW also regulates construction or work above the OHWM if it will use, divert, obstruct, or change the natural flow or bed of state waters (77.55.011(11)).

[34] In July 2015, WAC 220-660-370(4) replaced WAC-220-110-280 and WAC 220-110-285. The change in regulations resulted in no change to the allowed locations of single-family residence bulkheads in saltwater areas (i.e., single-family residence bulkhead processed under RCW 77.55.141).

associated marine shoreline armor projects. First, we evaluated the completeness and quality of permits and associated application materials for structure location and length. We then evaluated implementation of those permits by measuring these structural dimensions after completion of the constructed projects. Further, we applied the Marine Shoreline Design Guidelines (MSDG, Johannessen et al. 2014) to shoreline armor projects to compare permitted versus recommended structure design. We describe our methods and summarize key results of implementation monitoring conducted from 2014 through 2016. This report also describes unforeseen challenges encountered throughout the course of assessing the HPA permitting process and potential opportunities for growth and accountability within WDFW, project managers, and coastal landowners.

Methods

Permit and Survey Site Selection

There are many project types, armor designs (Figure 4.1) and permit classes (e.g., emergency permits) of shoreline armor in Puget Sound. For our review, we focused efforts on single-family residences constructing three project types: 1) new structures, on previously unarmored shoreline; 2) structure extensions, either in length or waterward additions to previously armored shoreline; and 3) replacement of previously armored shoreline. We concentrated only on standard HPA permits, eliminating review of special permits for emergency projects. Finally, we only surveyed completed projects.

Figure 4.1. Images of various hard armor designs. Top left: concrete wall with ecology block groins; top right: vertical wood wall; bottom left: anchored log and vertical wood piles; bottom right: rock revetment

During 2014 we cooperated on a project that monitored only Kitsap and San Juan counties to identify and evaluate shoreline armor projects permitted from January 2006 to September 2014 (Dionne et al. 2015).

"Monitoring years" 2015 and 2016 included permits issued between October 2014 and September 2015, and from October 2015 to September 2016, respectively, and expanded efforts to include all Washington coastal counties (including the Pacific coast) as potential sampling areas.

We identified shoreline armor projects to monitor using WDFW permit databases: the Hydraulic Permit Management System (HPMS) (2014) and the Aquatic Protection Permitting System (APPS) (2015-2016). Both databases store all application material associated with HPA permits: the permit, plans, maps, photographs, reports, correspondence between WDFW and the applicant, etc. The HPMS and APPS were not developed to support data query and analysis, but rather to track permit applications and processing. Nevertheless, these permit databases represent the most comprehensive and detailed data on shoreline armoring projects in Puget Sound, and they are the only such databases within WDFW.

Within both permit databases, most of a project's information is held in static digital files that do not enable focused electronic searches, and consequently, obtaining all relevant shoreline armoring projects in HPMS or APPS required broad search criteria that yielded many project types outside our intended scope. As a result, substantial "manual" effort was needed to sort the various permit and project types generated by our queries. For example, marine shoreline armor permits are stored in APPS as either: a) "shoreline armoring – marine"; b) "bank protection", a project type that includes freshwater bank protection; or c) "other", which includes myriad permit types. Further, HPMS and APPS did not enable electronic searches by project type (i.e., new, extension, replacement, or repair), and HPA project types are not used consistently in the databases. Our monitoring efforts were limited to new, extension and replacement projects only, however HPA permits are required for *all* activities in or along marine waters. Therefore, we completed initial reviews of all potential projects to accurately select and index HPA permits for new, extension and replacement projects only (e.g., excluding vertical capping of existing armor or minimal surface repairs). Additionally, HPMS and APPS does not track project construction status, and the permitting habitat biologists may sometimes be unaware of a project's status. Because implementation monitoring relied on surveying completed projects, we contacted landowners or their authorized agents to determine construction status. Finally, only standard permits for marine shoreline armor, new/extension/replacement, confirmed to be completed were included as potential candidates for implementation monitoring.

Data Collection

Data collection consisted of two major steps: 1) recording information from the HPA permit and associated application information, and 2) taking measurements at the project site.

Information from Permits. Preliminary permit review and data compilation was the initial step in implementation monitoring. We accessed permits and supporting application materials (e.g., JARPA, geotechnical report, construction plans) digitally from HPMS and APPS. We recorded identifying information for each permit including:

- Applicant, landowner, and/or authorizing agent information
- Location address, coordinates, and parcel ID (if available)
- Permit issue and expiration dates
- Permitting biologist information

HPA permits for marine shoreline armor specify how, when, and where a project is to be carried out. These project provisions, which allow or restrict shoreline activities, are specified in either the HPA permit text or supporting application materials (e.g., project plans), and can vary depending on project type, local environmental conditions, and affected infrastructure. Our implementation monitoring encompassed a suite of measurable and observable project provisions and conditions. However, this report evaluates only two critical structural dimensions of shoreline armor:

- Length (ft.) of permitted armor (Figure 4.2)
- Location of permitted armor (Figure 4.3), described as:
    a. Hydraulic code rule. Noted as a location relative to ordinary high water (for new projects) or relative to existing armor structure (for replacement projects).
    b. Elevation (ft. from mean lower low water [MLLW]) at toe of armor[35]. Noted as an exact elevation (e.g., 12ft above MLLW), a minimum vertical distance relative to an exact elevation (e.g., > 12ft MLLW), or a minimum vertical distance relative a fixed tidal datum (e.g., ≥ MHHW);
    c. Waterward distance (ft) of armor face relative a fixed and measureable location. Noted as a horizontal distance from an upland feature (e.g., 6ft waterward of upland deck), a waterward structure (e.g., nine feet landward of permanent stake), or an adjacent structure (e.g., no farther waterward than adjacent bulkhead).

For dimensions not provided in the permit text (i.e., when a permit refers to a project's plans), we obtained values from project plans or other application material under the assumption that such documentation was accurate, up-to-date, and approved. If dimensions were not provided but were discernable on project plans drawn to scale, then we measured those dimensions with a ruler. For both length and location, we recorded information source as either HPA permit, project plans, or not provided. Dimensions that could only be obtained by measuring from plans were also classified as "not provided." Measurements of shoreline armor length and location are depicted in Figures 4.2 and 4.3, respectively.

Measurements at Project Site. The purpose of field surveys was to conduct on-site measurements of structure location (by elevation and/or distance from feature) and structure length.[36] Measurements were then compared with values in permit provisions or associated plans, and these comparisons were the basis for evaluating whether permittees met the provisions of their permits.

Data collection methods for structure location and length remained consistent from year to year. We determined structure location as elevations along base of the armor structure using a Trimble Geo XH 6000 Centimeter Edition RTK GPS unit (2-10 cm vertical accuracy). For sites where poor satellite coverage limited our ability to operate the GPS, we collected elevations using laser level and stadia rod. For sites where armor location was described as a distance from a reference point (e.g., benchmark or feature such as a building), we measured from the reference point indicated on the permit or plans to the waterward face of the structure (Figure 4.3). Some structures had location described by both elevation and distance. Armor length was determined by measuring along the structure from end-to-end (Figure 4.2).

Elevations collected using the GPS were recorded in North American Vertical Datum 1988 (NAVD88). However, most permits referenced elevations relative to mean lower low water (MLLW). To convert all GPS-collected elevation points from NAVD88 to MLLW we used the NOAA software package, Vertical Datum Transformation (VDatum), designed to transform coastal elevation data to desired elevation output following selected vertical (datum) and horizontal (coordinate system) sources (NOAA 2012). For select sites where lack of satellite reception inhibited GPS elevation readings, we used the elevation of the waterline (+/-ft MLLW) as a benchmark for subsequent laser level and stadia rod measurements.

[35] Where base of armor structure meets beach face.

[36] Additional information on permit provision compliance and forage fish beach habitat was recorded in the field, but not included for the purposes of this report.

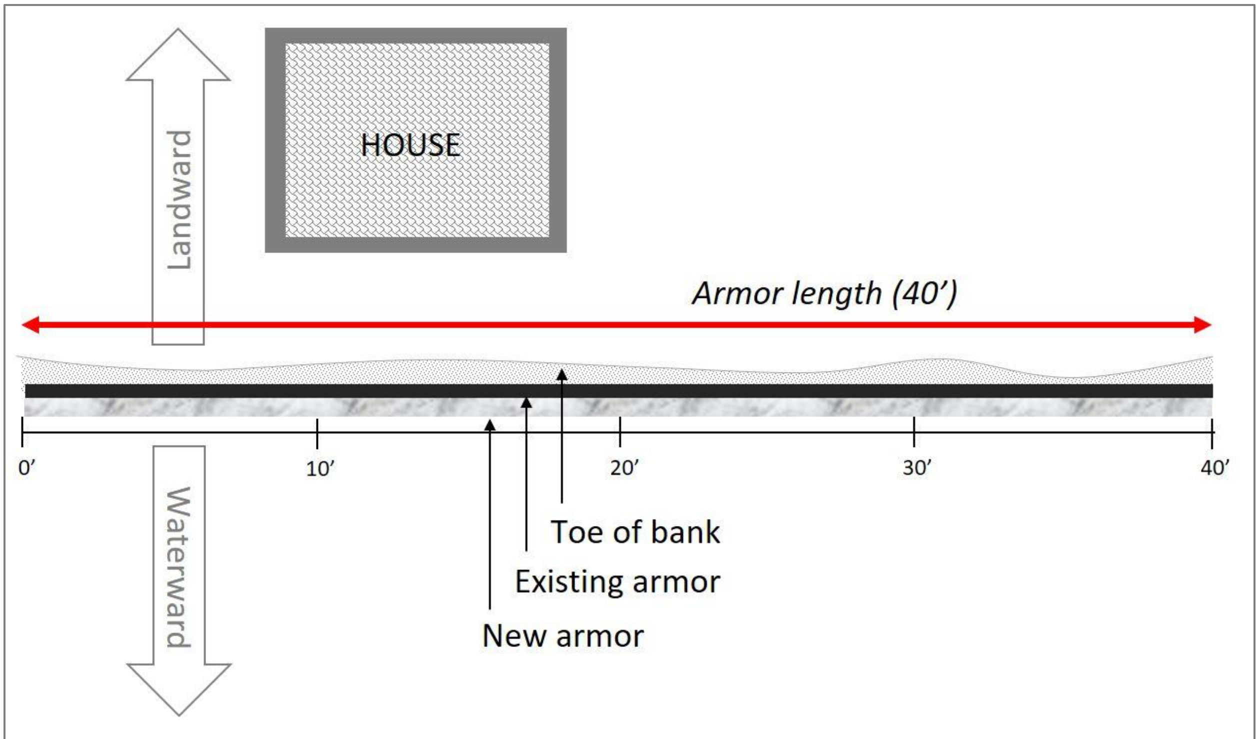

Figure 4.2. Overhead view of hypothetical HPA project site depicting measurement of shoreline armor length. Schematic simplifies location of replacement armor relative to existing armor and toe of bank. Red line denotes armor length measured.

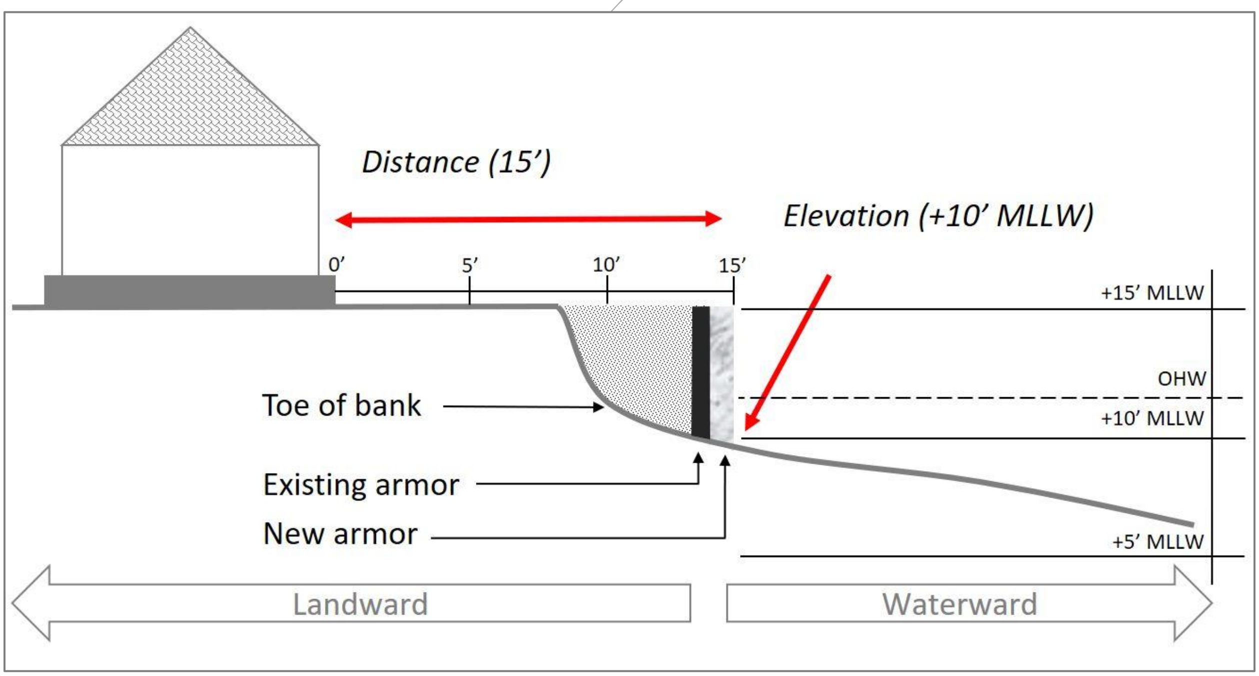

Figure 4.3. Profile view of hypothetical HPA project site depicting measurement of shoreline armor location. Schematic simplifies location of replacement armor relative to existing armor and toe of bank. Red lines denote armor location measured as either a waterward distance from a feature or an elevation at toe of structure (i.e., where base of armor wall meets the beach).

Waterline elevations were obtained from nearest NOAA tide prediction station, and adjusted for during post-processing with respect to verified tide height.

MSDG Assessment. We took additional steps to evaluate how HPA permitted project designs compared to project design recommendations derived from the Marine Shoreline Design Guidelines (MSDG, Johannessen et al. 2014). The MSDG was published by a collective of state agencies to facilitate effective best-management approaches in site-specific shoreline protection. The MSDG was developed to provide a comprehensive framework for site assessment and alternatives analysis to determine the need for shoreline protection and identify the technique that best suits the conditions at a given site (Johannessen et al. 2014). The MSDG's systematic approach for selecting the most appropriate type of protection is based on managing risk to buildings and infrastructure posed by shoreline erosion. The MSDG can inform use of "the least impacting technically feasible alternative" for shoreline protection as required by Hydraulic Code Rules (WAC 220-660-370). Following the MSDG cumulative risk model, we collected information on the following parameters:

- Erosion potential
    - Shore type – landform type designated by Ecology (2010)
    - Fetch – distance (miles) over which wind can blow unimpeded and form waves, as measured from online Coastal Atlas (Ecology 2010)
- Infrastructure threat
    - Setback determination – linear measure (ft) from bank crest to waterward most upland infrastructure, as provided or measured from permit documentation
    - Infrastructure type – as determined from permit documentation

Data Analysis

Data analysis from marine shoreline armor monitoring were done in Excel.

Quality of HPA Permit. We evaluated permittor implementation by assessing the quality of HPA permits. We expected permits to include provisions for two critical structure dimensions (i.e., armor location and length) and to conform with Hydraulic Code Rules. Our review included project plans, which were usually were referenced by a permit provision, and other permit application materials.

For a new armor project, an HPA permit conforms with the Hydraulic Code Rules (WAC 220-660-370) when it requires the structure be located no farther than six feet waterward of ordinary high water at the site. For an extension or replacement projects, an HPA permit conforms with the WAC when it requires the structure be located no farther waterward than the pre-existing structure or waterward but directly abutting the pre-existing structure. We determined HPA permits to not conform with the WAC when the permit made no or insufficient mention of OHW (for new projects) or pre-existing structure (for extension and replacement projects).

For all projects, we used the MSDG to calculate cumulative risk scores based on estimates of erosion potential and infrastructure threat, and determined risk categories as low (0-15), moderate (16-36) and high (>36). We used risk categories and associated site parameters (i.e. wave energy, beach alignment and backshore width) to determine MSDG recommended armor design. Design recommendations at low risk sites included armor removal or no action. Design recommendations at both moderate and high risk sites were largely based on site-specific conditions, and varied between no action, beach nourishment, planting vegetation, placing large woody debris (LWD), hard armor, and relocation of upland infrastructure. We then compared MSDG recommended designs with HPA permitted designs to determine the degree of consistency between them.

Structure designs for shoreline stabilization range across a spectrum of hard, soft and natural techniques, and individual techniques can be used alone or in combination. Hard armor methods utilize static structures built parallel to the shoreline, such as riprap revetments, vertical concrete, or artificial sheetpiles. Soft armor methods utilize strategically placed natural materials to mimic the beach environment, such as beach nourishment and log placement. Natural methods utilize passive or preventative measures before additional armor is needed, such as planting vegetation, utilizing effective drainage or relocating upland infrastructure. For the purposes of our assessment, we defined all MSDG recommended designs as either natural (i.e., removal, relocation, or no action), soft armor (i.e., beach nourishment, or LWD) or hard armor, and all HPA project designs as either soft armor or hard armor. Note that because our study included only HPAs for shoreline armor addition (i.e., new and extension projects) or alteration (i.e., replacement projects), we did not look at permits for armor removal or infrastructure relocation. Therefore, our assessment includes no HPAs issued for natural designs.

Quality of Hydraulic Structure Construction. We evaluated the quality of project implementation through a ratio of field-measured structural dimensions to permitted dimensions called Implementation Error (IE):

$$IE = (m - p)/p \bullet 100$$

where p is the permit specified dimension and m is the measured actual dimension of the structure. A negative IE for length denotes a structure measured shorter than permitted, and a positive IE denotes a structure measured longer than permitted. However, a negative IE for location elevation denotes a structure measured further waterward than permitted and a positive IE denotes a structure measured farther landward. For projects noting "no further waterward than adjacent armor" as their location, we made visual assessments of relative position on-site and designated an IE of 0.0 when the structure was neither waterward nor landward of permitted location.

For each project, we calculated an implementation error for structure location (by known elevation and/or relative distance) and structure length. We binned values of implementation error into four categories: <10%, 10-20%, 20-30% and >30%. For our purposes, we considered a project to be consistent with their permit when measured at or landward of permit-provisioned location or at or shorter than permit-provision length, regardless of implementation error. For some analyses we applied a hypothetical 10% tolerance to the permitted structural dimensions.

Many permits or project plans describe structure location relative to OHW or to the pre-existing structure (i.e., relative to OHW for new projects, or relative to pre-existing structure for replacement projects). During construction, the mark of OHW or the pre-existing structure are usually altered or obliterated. Hence, because all surveys of HPA projects were conducted post-construction, a permittee's consistency with permitted location relative to OHW or pre-existing structure could not be determined. That is, we could not determine the permittee's consistency with permit provisions that relied on site-specific OHW or the pre-existing structure. However, most project plans describe structure location other ways as well, such as elevation relative to MLLW or distance from an upland feature. We could determine IE for these structures.

Results

For monitoring years 2014, 2015 and 2016, we identified 134, 226, and 128 shoreline armor projects, respectively, from the two HPA databases. After selecting standard HPAs issued for new, extension and replacement armor projects on marine shorelines, we identified 48, 119 and 107 potential permits in 2014, 2015 and 2016, respectively (Appendix, Table C-1).

Box 4.1. Examples of sufficient structure location information determined from permits and supporting application material.
10.0 (ft) MLLW/(m) NAVD88
2.0 (ft) < MHHW
At MHHW
5.0 (ft) landward [fixed upland location]
No further waterward than adjacent bulkhead

The number of project sites we were able to survey from 2014 to 2016 differed among years due to budgetary constraints, site accessibility, and other practical considerations. In 2014, we completed 31 field surveys of HPA-permitted and constructed hard armor projects throughout Kitsap and San Juan Counties (Figure 4.4). In years 2015 and 2016, we expanded survey opportunity to all coastal counties, however, no surveys were done in Grays Harbor, Jefferson, Snohomish and Whatcom counties. We completed 11 and 27 field surveys in 215 and 2016, respectively

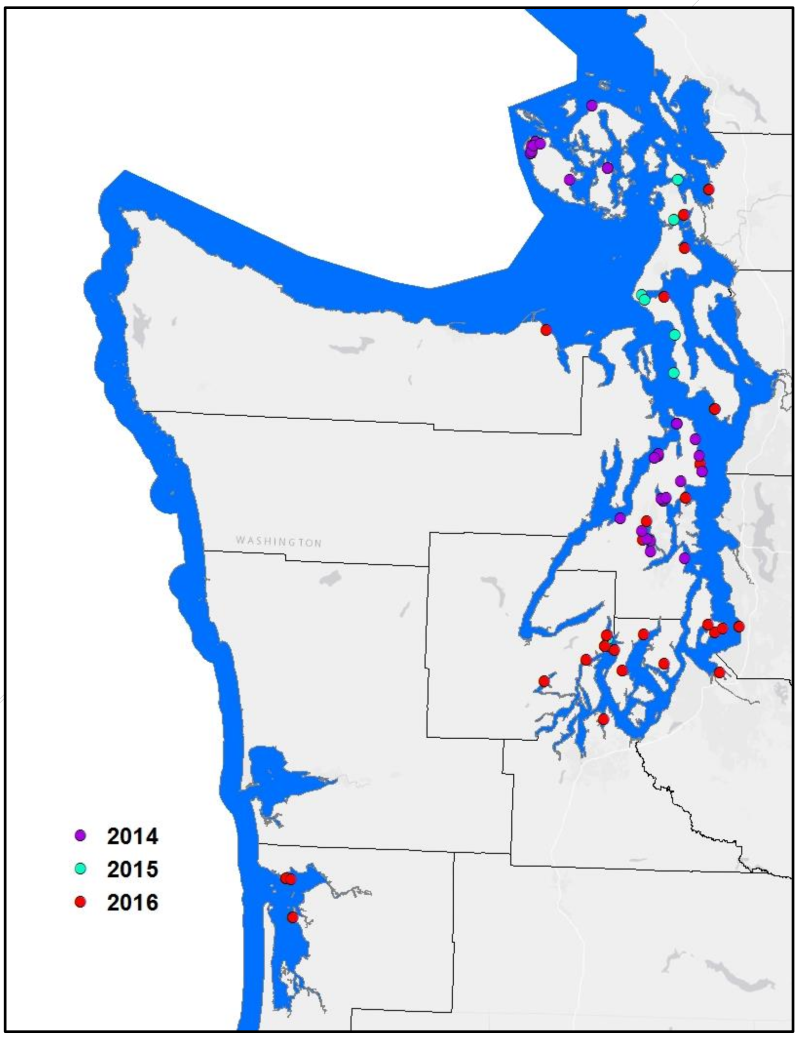

Figure 4.4. Location of marine shoreline armoring projects included in implementation monitoring from 2014 to 2016.

(Appendix, Table C-2). Replacement projects were either the majority or plurality of types surveyed annually: 55% (n=17) in 2014, 45% (n=5) in 2015, and 67% (n=18) in 2016 (Table 4.1). Across all monitoring years, we surveyed 22 new, 7 extension, and 40 replacement projects for consistency with their HPA permit or Hydraulic Code Rules (Table 4.1).

Table 4.1. Count of marine shoreline armor projects included in implementation monitoring by type and year surveyed.

	Monitoring Year			
Project Type	**2014**	**2015**	**2016**	**Total**
New	12	3	7	22
Extension	2	3	2	7
Replacement	17	5	18	40
Total	31	11	27	69

Quality of HPA Permit

During our initial project review of HPA permits and supporting application material, we identified several projects unsuitable for evaluation of the shoreline structure because they lacked any information (even that which could be measured from plans) with which to assess consistency of the structure with its permit (Box 4.1, 4.2). As a result, we eliminated these projects from field survey effort or any further assessments. In total, 6 of 48 projects (13%) in 2014, 5 of 119 projects (4%) in 2015, and 12 of 107 projects (12%) in 2016 were eliminated from implementation monitoring because they lacked sufficient structure location and length information (Appendix, Table C-1).

Of 69 marine shoreline armor projects surveyed from 2014 to 2016, 71% specified provisions for both critical structure dimensions (location and length) in the HPA permit *or* supporting application material. Twenty-nine percent of 69 surveyed projects did not include HPA provisions for critical structural dimensions, and hence, that information was measured from project plans.

We found that the sources of information (i.e., provided in HPA permit or in supporting application material) varied widely between structure length and location, but that this variability was consistent among monitoring years and project types. Structure length was stated in HPA permit provisions for 83% (n=57) of projects, stated in supporting application material for 13% (n=9) of projects, and not provided for 4% (n=3) of projects (Table 4.2). In contrast, structure location was stated in HPA permit for only 4% (n=3) of projects, stated in supporting application material for 71% (n=49) of projects, and not provided for 25% (n=17) of projects (Table 4.2). In other words, information for length was usually found in permit provisions, but information on location was usually found in the supporting application material.

Box 4.2. Examples of insufficient structure location information determined from permits and supporting application material.

No further waterward than existing bulkhead

No further than 6.0ft waterward of bank toe

Above OHW

Below MHHW

Box 4.3. Examples of OHW relative location information determined from permit provisions and application material.

Face of new bulkhead

Toe of new bulkhead

Toe of existing bank

Waterward new bulkhead

Box 4.4. Examples of structure relative location information determined from permit provisions and application material.

No further waterward than existing bulkhead

No further than +/-#.#ft waterward of existing bulkhead

At existing bulkhead face

Of 22 new armor projects surveyed in 2014, 2015 and 2016, 17 described structure location relative to ordinary high water. In other words, for 17 projects, permits were written consistent with the rule for structure location (i.e., no further than six feet waterward OHW or toe of bank [WAC 220-660-370]). Of these 17 projects, 2 stated the location relative to OHW on the HPA permit, 13 stated location relative to OHW on the supporting application material, and 2 did not explicitly state location but the structure's location relative to OHW was estimated from the application material. However, the majority of projects also specified the location of OHW as distance relative to a non-permanent structure (e.g., toe of existing bank [Box 4.3]). Consequently, for 11 of 17 projects, actual structure location relative to OHW could not be determined at time of our site visits (Appendix, Table C-6). Fortunately, nearly all new armor projects also provided structure location relative to MLLW.

For 47 armor extension or replacement projects surveyed in 2014, 2015 and 2016, the structure's location was described consistent with hydraulic code rule (i.e., no farther waterward than the pre-existing structure [WAC 220-660-370]). Of these 47 permits, 34 stated location relative to the pre-existing structure on the HPA permit and 13 stated location relative to the pre-existing structure in supporting application material (Box 4.4) (Appendix, Table C-7). However, similar to OHW, because the pre-existing structure's location was altered or obliterated during construction, the actual location of the resulting structure could not be determined using the pre-existing structure. Fortunately, nearly all armor extension or replacement projects also provided structure location relative to MLLW.

Table 4.2. Source of structure location and length specifications by monitoring year and project type as either: HPA permit, application materials such project plans, or not explicitly provided but could be measured from project plans.

		Monitoring year			Project type			
Dimension	**Source**	**2014**	**2015**	**2016**	**New**	**Extension**	**Replacement**	**Total**
	HPA permit	2	1	0	1	0	2	3
Location	Application material	26	6	17	17	4	28	49
	not provided	3	4	10	4	3	10	17
	HPA permit	24	10	23	16	6	35	57
Length	Application material	5	1	3	4	1	4	9
	not provided	2	0	1	2	0	1	3
	Total	31	11	27	22	7	40	69

All HPA permits (including the supporting application materials) provided location either by known elevation[37] or by relative distance. However, the quality of the information related to structure location varied among projects. Of all 69 projects, 29 provided structure location by known elevation only, 6 provided structure location by relative distance only, and 34 provided structure location by both known elevation and relative distance (Table 4.3). Of projects surveyed in 2014, the majority (22 of 31) provided location by elevation only (Table 4.3). This shifted in 2015 and 2016 when the majority of projects provided both known elevation and relative distance. Looking at structure location by project type, across all years, we found that for new armor the majority of projects provided location by elevation

[37] For projects providing known elevation as tidal datum MHHW only, we used VDatum (NOAA, 2012) to determine site-specific elevation (+ft MLLW) of MHHW.

only (14 of 22), but for extension and replacement armor the majority of projects provided location by both a known elevation and relative distance (Table 4.3). Structure locations provided as a known elevation at armor toe ranged from approximately +6ft MLLW to +15ft MLLW, depending on individual project, with the majority (68%, n=43) located at greater than +10ft MLLW.[38]

Quality of Hydraulic Structure Construction

Structure Location. Of 69 projects surveyed in 2014, 2015, and 2016, 67% met the permit's specification for structure location. That is, the structures were equal to or landward of the specified location. With a 10% tolerance, that percentage increased to 83%. The percentage of projects meeting permit specifications for location increased over time: 55%, 73%, and 78% in 2014, 2015, and 2016, respectively. With a 10% tolerance, these percentages increased to 81%, 100%, and 81%. The percentage that met permit specification for location did not vary much by project type: 64%, 57%, and 70% for new, extension, and replacement projects, respectively (Table 4.4).

Of 63 projects that provided structure location by known elevation (+/-ft MLLW), 6% (n=4) were constructed exactly as specified in the permit or application material (IE = 0%), 60% (n=38) were constructed farther landward, and 33% (n=21) were constructed farther waterward than specified (Table 4.4). The proportion of structures built more waterward than allowed by their permit decreased over time at 45%, 27%, and 19% in 2014, 2015, and 2016, respectively. The proportion of structures built farther waterward than allowed by their permit did not vary drastically among new (38%), extensions (23%) and replacement (31%) projects (Table 4.4). However, of these, 21 structures that were measured waterward, 48% had implementation errors less than 10%. Similarly, of the 38 projects with structure location measured landward of permitted location, 58% had implementation errors less than 10% (Figure 4.5).

For those six projects in 2016 where structure location was measured using relative distance only, we found that one replacement was constructed as specified by permitted location, one new and two replacement projects were constructed landward of permitted location, and one extension and one replacement project were constructed waterward of permitted location. However, only one extension project was constructed waterward of permitted location by an IE of greater than 10% (Table 4.4).

Of the 34 projects for which armor location was specified by both known elevation and relative distance, we found that IEs for these two permit specifications were within 10% of each other for only nine projects (Appendix, Figure C-1). In other words, for most projects, there was little agreement between locations using the two measures. Of seven projects where elevation measures in field determined that the structure was constructed waterward of the permitted location by a IE of >10% , relative distance indicated that five projects had a waterward IE of 0%, one had a waterward IE of 0-10%, and one was landward with an IE of 20-30%. Conversely, of two projects where relative distance measures in field identified that the structure was constructed waterward of permitted location by an IE of >10%, elevation measures identified that both were landward with IEs of 0-10% and 10-20% (Appendix, Figure C-1).

Structure Length. Individual projects lengths ranged from 30 ft to over 800 ft of shoreline armor, with the majority (52%, n=36) permitted >100ft. Implementation errors of permitted versus measured structure length were calculated for each of 69 field-surveyed projects. We found that 43% (n=30) of project lengths were measured on-site as longer than permitted. However, of these 30, the IE was less than 10% for 21 structures (Table 4.5, Figure 4.6). Of the nine projects measured longer than permitted by greater than 10% IE, six were for new armor construction (Table 4.5).

[38] MHHW is located at +11.36ft MLLW in Seattle. In general, elevation of MHHW (+ft MLLW) increases Southward and decreases Northward (NOAA, 2013).

Table 4.3. Count of surveyed projects with armor structure location provided as a known elevation or relative distance by monitoring year and project type.

	Monitoring year				Project type			
Location Type	**2014**	**2015**	**2016**	**Total**	**New**	**Extension**	**Replacement**	**Total**
Elevation only	22	3	4	29	14	2	13	29
Distance only	0	0	6	6	1	1	4	6
Both	9	8	17	34	7	4	23	34
Total	31	11	27	69	22	7	40	69

Table 4.4. Count per implementation error (IE) category of projects measured for structure location by monitoring year and project type. Structures were either equal to (IE < 1%), landward, or waterward of permitted location by known elevation (+/-ft MLLW). Values in parenthesis are count of projects measured on-site that provided only location by relative distance (ft).

		Monitoring year				Project type			
Relative location	**IE category**	**2014**	**2015**	**2016**	**Total**	**New**	**Extension**	**Replace-ment**	**Total**
Equal	0%	2	2	1 (1)	5 (1)	1	1	3 (1)	5 (1)
Landward	< 10%	11	3	9 (2)	23 (2)	11 (1)	2	10 (1)	23 (2)
	10 - 20%	3	1	9 (1)	13 (1)	1	1	11 (1)	13 (1)
	20 - 30%	0	0	2	2	0	0	2	2
	> 30%	0	1	1	2	1	0	1	2
Waterward	< 10%	8	3	1 (1)	12 (1)	5	1	6 (1)	12 (1)
	10 - 20%	6	0	3 (1)	9 (1)	1	2 (1)	6	9 (1)
	20 - 30%	1	1	0	2	1	0	1	2
	> 30%	0	0	1	1	1	0	0	1
	Total	31	11	27 (6)	69 (6)	22 (1)	7 (1)	40 (4)	69 (6)

Table 4.5. Count of projects per implementation error (IE) category by monitoring year and project type. Structures were either equal to, shorter, or longer than permitted length.

		Monitoring year				Project type			
Relative length	**IE category**	**2014**	**2015**	**2016**	**Total**	**New**	**Extension**	**Replace-ment**	**Total**
Equal	0%	5	1	2	8	3	1	4	8
Shorter	< 10%	10	3	5	18	4	1	13	18
	10 - 20%	0	1	4	5	0	1	4	5
	20 - 30%	2	0	3	5	1	2	2	5
	> 30%	0	0	3	3	0	0	3	3
Longer	< 10%	10	2	9	21	8	1	12	21
	10 - 20%	1	3	0	4	2	1	1	4
	20 - 30%	3	0	0	3	2	0	1	3
	> 30%	0	1	1	2	2	0	0	2
	Total	31	11	27	69	22	7	40	69

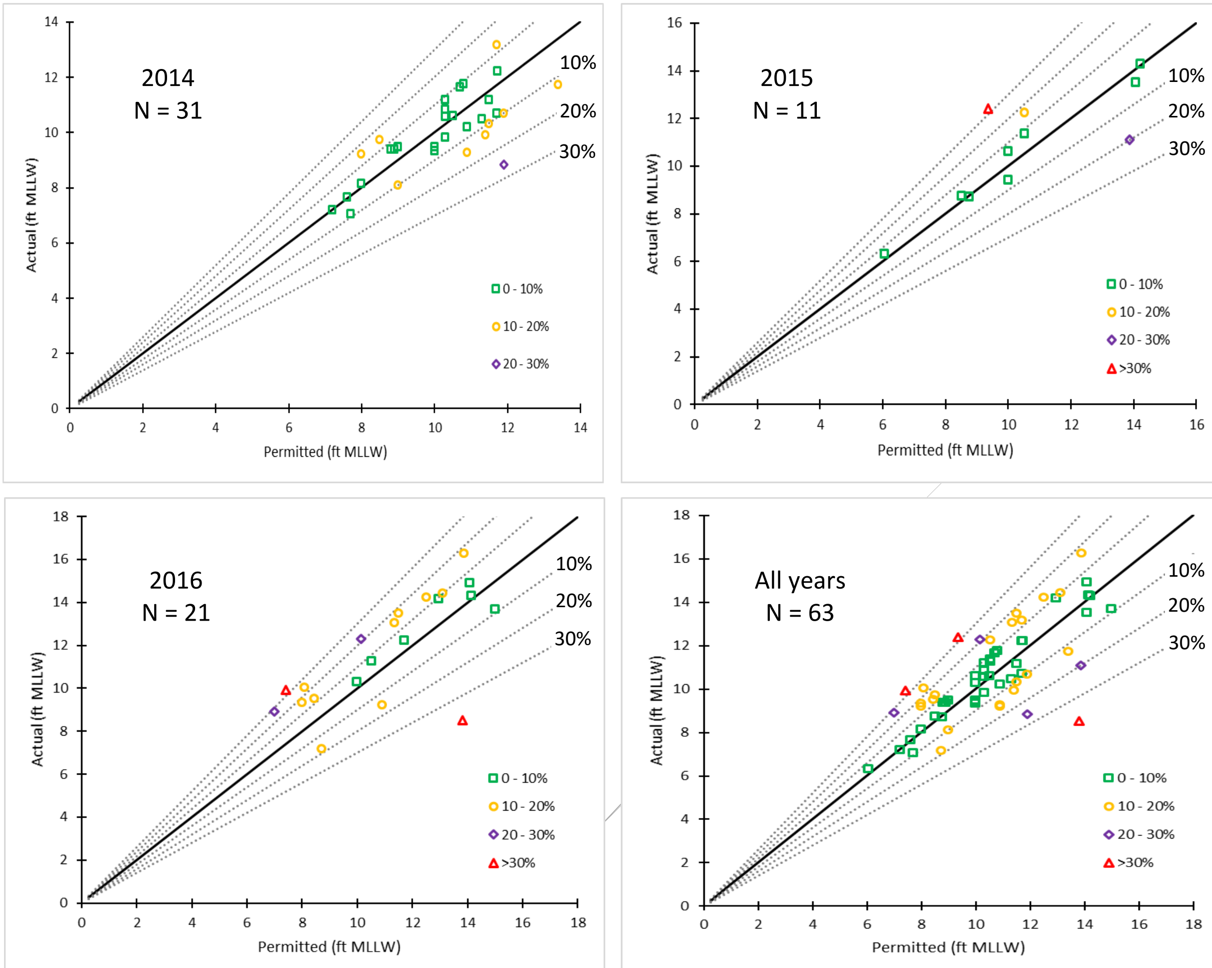

Figure 4.5. Comparison of marine shoreline armor structure location by known elevation (+/-ft MLLW) obtained from permit and application material (x-axis) and measured "actual" on-site (y-axis). Permitted location equals actual location on solid 45° diagonal line. Dotted lines represent different levels of implementation error binned into four categories 0-10% (green square), 10-20% (yellow circle), 20-30% (purple diamond) and >30% (red triangle). N is the number of projects that had specification for armor location in permit text or project plans.

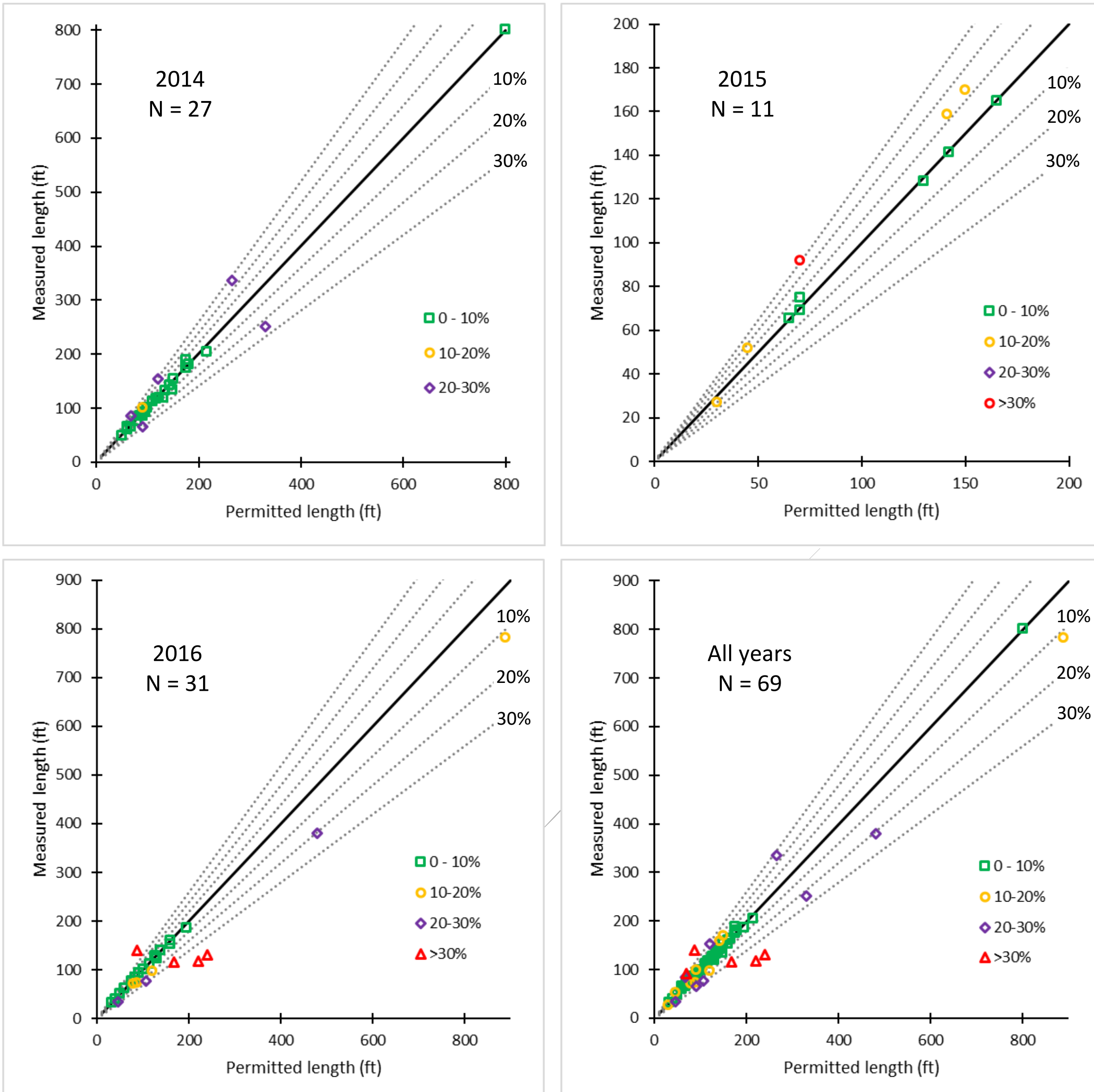

Figure 4.6. Comparison of marine shoreline armor structure length (ft) obtained from permit and application material (x-axis) and measured “actual” on-site (y-axis). Permitted length equals actual length on solid 45° diagonal line. Dotted lines represent different levels of implementation error binned into four categories 0-10% (green square), 10-20% (yellow circle), 20-30% (purple diamond) and >30% (red triangle). N is the number of projects that had specification for armor location in permit text or project plans.

MSDG Risk Assessment

We completed MSDG risk assessments on a total of 85, 44 and 29 permits in monitoring years 2014, 2015, and 2016, respectively. Across all surveys years, the majority of projects (63%, 100 of 158) were determined as moderate risk sites, followed by 54 (34%) projects determined as low risk, and only 4 (3%) determined as high risk (Figure 4.7, Appendix Table C-5). Among the moderate risk sites, 64% (n=64) of permits were issued for armor replacement projects, 27% (n=27) for new armor projects and the remaining 8% (n=8) for armor extension projects. Similarly among low risk sites, 65% (n=35) were issued for armor replacement projects, followed by 26% (n=14) for new armor projects, and 9% (n=5) for armor extension projects (Figure 4.8, Appendix, Table C-5).

Cumulative risk scores were used to determine MSDG recommended armor techniques for each project. Of 158 total projects, hard armor was recommended for 71, soft armor was recommended for 28, and natural technique was recommended for 59 (Appendix, Table C-3 and Table C-4). We then compared MSDG recommended techniques to HPA-permitted designs. We found that overall, 71 (45%) HPA project designs were consistent with MSDG recommendations and 87 (55%) HPA project designs were inconsistent with MSDG design recommendation. Of the 87 inconsistent HPA project designs, 83 were designed consistent with greater site risk (i.e., "over-armoring") and 4 consistent with lesser site risk (i.e., "under-armoring") than the MSDG recommendations. For those HPA projects that were designed consistent with greater site risk, we found that 2014 projects exhibited the greatest proportion of disparity, at 68% (n=58). This proportion decreased with 2015 projects at 36% (n=16) and 2016 projects at 31% (n=9). However, for those same inconsistent projects we did not find substantial differences amongst project types with 48% (n=21), 54% (n=7), and 54% (n=55) for new, extension, and replacement armor, respectively, assuming greater risk than the MSDG recommendations. Across all projects, the greatest proportion of disparity between HPA-permitted and MSDG-recommended designs were consistently seen at low risk sites, at an overall rate of 98% (n=53), and followed by moderate risk sites at an overall rate of 34% (n=34). For all four high risk sites, permitted project designs were consistent with MSDG recommendations (Table 4.6).

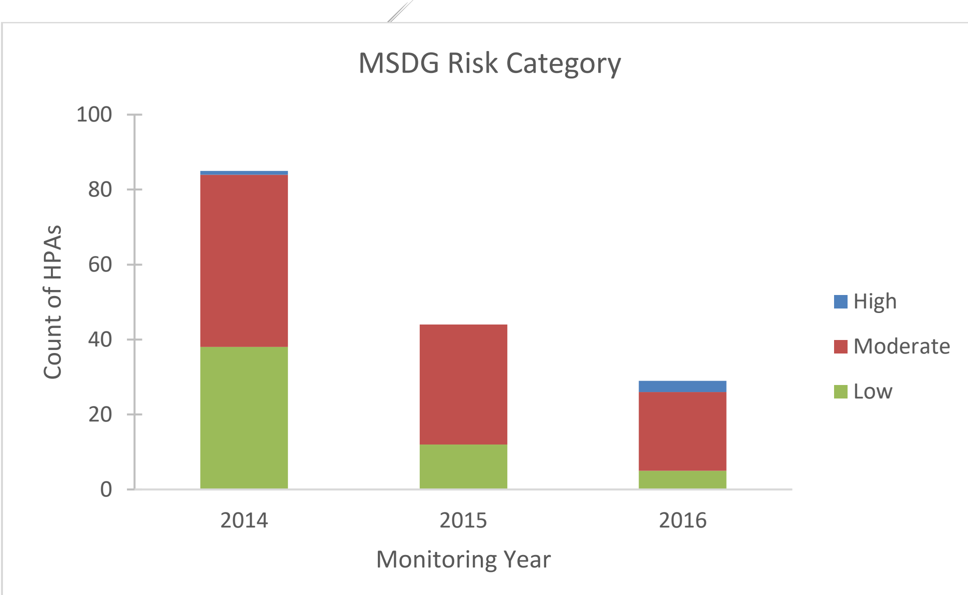

Figure 4.7. Count of HPA projects reviewed for MSDG risk category designation by each HPA monitoring year.

Figure 4.8. Count of HPA projects reviewed for MSDG risk category designation by HPA project type.

Table 4.6. Comparison of HPA-permitted shoreline armor design versus MSDG recommended design. Values are number of projects. > means HPA design harder than MSDG recommendation. < means HPA design softer than MSDG recommendation.

		Project Risk Comparison			
		HPA = MSDG	**HPA > MSDG**	**HPA < MSDG**	**Total**
Monitoring year	2014	24	58	3	85
	2015	28	16	0	44
	2016	19	9	1	29
	Total	71	83	4	158
Project type	New	19	21	4	44
	Extension	6	7	0	13
	Replacement	46	55	0	101
	Total	71	83	4	158
MSDG risk category	Low	1	53	0	54
	Moderate	66	30	4	100
	High	4	0	0	4
	Total	71	83	4	158

Discussion

The purpose of implementation monitoring of the HPA permitting process for marine shoreline armor was to provide a "report card" to managers and policy makers that: identifies potential areas of improvement in the permitting process for both WDFW and permittees, provides information on how well the permittees are meeting permit provisions, informs hydraulic project designs that support protection of fish life and shoreline processes, and builds a foundation to support ongoing adaptive management.

Implementation monitoring evaluates both the permittor (i.e., does the permit contain all necessary provisions and are the provisions consistent with Hydraulic Code Rules) and the permittee (i.e., did the permittee follow permit provisions), because successful projects depend on the behavior of both. Poor implementation of the permitting process by the permitting agency can lead to poor outcomes for both fish life and the landowner, even when the permittee follows the permit. By evaluating the performance of each, we might identify areas of success and opportunities for improvement in the overall process.

Results Summary

Permit Quality. Complete permits (i.e. one that contains provisions and/or project plans for all critical structural dimensions) were issued for most projects. Out of 69 marine shoreline armor projects surveyed from 2014 to 2016, 71% contained specifications for the critical structure dimensions of armor length and location in the HPA permit, project plans, *or* supporting application material. Moreover, 93% of HPA permits were written consistent with the rule for structure location (i.e., no further waterward OHW or toe of bank for new construction and no further waterward than pre-existing structure for extension or replacement construction). However, OHW is a useless landmark for post-construction monitoring or permit enforcement. OHW is often obliterated during construction, and due to the dynamic nature of OHW[39] and the subjectivity of OHW identification, measuring structure location relative to OHW is unlikely to yield repeatable results.

The source of information (permit, plans, application materials) for critical structural dimensions and the language describing critical structure dimensions varied among permits and project plans. Consequently, more effort than anticipated was needed to glean key information from permits. For the 69 projects surveyed for implementation, essential project information was either stated in HPA permit provisions, stated in supporting application material (such as plans or JARPA), or not provided but measured by us from project plans. Further, structure location was conveyed as either an elevation, a relative distance, or both. Projects providing location by both elevation and distance often exhibited inconsistency between the two locations, and this necessarily resulted in an implementation error for at least one of those specifications. Clearly and prominently stated standardized permit provisions or requirements for submitted project plans, especially for structure location, would improve communications between permittor and permittee, minimize misunderstandings about the proposed location of a structure, and reduce conflict during post-construction site inspections.

Shoreline Armor Quality. Forty-three percent of 69 structures were measured longer than permitted length. With a 10% tolerance this value improved to 13%. Thirty-three percent of 69 structures were measured waterward of permitted location. This percentage improved over time: 48%, 36%, and 19% in 2014, 1015, and 2016, respectively.

MSDG. Shoreline armor designs permitted by WDFW often did not align with MSDG-recommended designs. MSDG-recommended designs encourage shore protection most appropriate for site-specific shoreline processes (Johannessen et al. 2014). Of 158 HPA permits reviewed for project design, over half

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[39] The OHWM is the dynamic boundary between the aquatic and terrestrial environments and, in most cases, is not a static elevation (Anderson et al. 2016).

(53.8%) were inconsistent with MSDG design recommendations, indicating most HPA-permitted structures were over built relative to local shoreline processes and to the actual risk of structural failure. Given concerns regarding ecological impacts of shoreline armor, regulators should encourage shoreline armor designs most appropriate for local erosion risk, and look for opportunities to work with project proponents on more soft techniques of erosion control.

<u>HPA database</u>. The HPA database(s) had limited data query capabilities. The small number of project types in the database, for example, required the implementation monitoring crew to manually filter hundreds of HPA permits that were not marine shoreline armor projects. This led to reduced efficiency and increased opportunity for subjective error when identifying HPA projects to monitor. The HPA database, even with its limitations, provides the most accurate and comprehensive data source to track and monitor shoreline armoring. It contains information on thousands of hydraulic projects throughout Washington. Therefore, improving the HPA database's data processing capabilities will benefit not only WDFW but other regulatory agencies and shoreline restoration organizations as well.

Management Recommendations

Shoreline erosion will continue to be major challenge in Puget Sound, as managers seek to balance natural geomorphic process and threats to coastal properties. In particular, as human population growth continues to demand shoreline development and the prospect of higher sea levels raises concern of increased erosion and damage (Shipman et al. 2010) this balancing act will become ever more important. The Washington Department of Fish and Wildlife, via the HPA permitting process, influences where, when, and how to armor a shoreline. Therefore, WDFW has the opportunity to address impacts of shoreline armor at a project's inception by requiring complete and accurate project information, a demonstrated understanding of appropriate site-specific erosion protection, and proper structure construction. WDFW should support rigorous assessments of armor effects on coastal processes and nearshore habitat, and encourage landowners to adopt armor designs with the least ecological impacts. We suggest the following main areas for improvement:

<u>Data management</u>. Develop an information management system, in coordination with regulatory and field staff, which allows for easier data extraction (e.g., project type, construction status) and programmatic review. Revise categories within database terminology (e.g., project type = new, extension, replacement) to facilitate more precise project identification.

<u>Hydraulic code rule</u>. Add language to WAC 220-660-370(6)(a) which may require a permittee to establish a measureable (horizontal) distance of a shoreline structure or ordinary high water from a fixed and permanent reference location (i.e. benchmark location) before starting work on the project. A permittee shall then provide standard description and documentation of: location and determination of ordinary high water for new armor construction, or; location of pre-existing structure for extension and replacement construction.

<u>Permit information</u>. Develop standard language of measurable parameters that describe critical shoreline armoring location and length in an HPA permit. Ensure that critical structural dimensions (location and length) are clearly specified in the HPA permit and associated application material. Confirm on the permit that structural dimensions are described in reference to another fixed location (e.g., known elevation, permanent structure) and that values are measurable on-site both before and after construction. Improve communications between all involved parties to make sure that understanding of project information and permit provisions are clear.

<u>Structure design</u>. Promote understanding and use of MSDG with various project proponents and decision-makers and area biologists. Advance internal use of MSDG local cumulative risk assessments to

inform site-specific best management practices for shoreline armoring. Track over time discrepancies between HPA permitted and MSDG recommended project designs to provide feedback.

Project monitoring. Increase and expand (resource and personnel) efforts in implementation monitoring of marine shoreline armor. Enhance efforts in effectiveness monitoring to evaluate impact of shoreline armor on nearshore beach process and function. Work with regulatory and research partners to advance monitoring efforts and communicate findings.

Staff trainings. Provide trainings for permitting and regulatory staff that standardize procedures and language for identifying, describing and measuring permit information (i.e., project type, armor location, structure length) which accurately reflect hydraulic codes rules and local best management practices for marine shoreline armoring.

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Appendices

Appendix A. Miscellaneous Data Summaries for Culverts

Table A-1. Number of culverts visited for implementation monitoring in each county per year.

	Monitoring Year						
County	**2013**	**2014**	**2015**	**2016**	**2017**	**Total**	**Percent**
San Juan	0	0	0	0	0	0	0.0
Island	0	0	0	0	0	0	0.0
Whatcom	2	4	5	8	6	25	9.5
Skagit	2	5	0	1	0	8	3.0
Snohomish	12	9	3	3	2	29	11.0
King	9	4	11	11	9	44	16.7
Pierce	4	2	3	5	2	16	6.1
Kitsap	3	4	7	4	1	19	7.2
Thurston	2	1	2	3	1	9	3.4
Mason	5	2	2	6	0	15	5.7
Grays Harbor	0	6	5	4	6	21	8.0
Jefferson	0	9	5	1	0	15	5.7
Clallam	3	4	2	2	2	13	4.9
Pacific	0	6	6	0	1	13	4.9
Lewis	10	2	1	1	2	16	6.1
Wahkiakum	0	2	0	0	1	3	1.1
Cowlitz	2	3	2	0	1	8	3.0
Clark	0	1	4	2	0	7	2.7
Skamania	0	0	0	1	0	1	0.4
Klickitat	0	0	0	1	0	1	0.4
total	54	64	58	53	34	263	100

Table A-2. Number of culverts measured for implementation monitoring during each month.

	Monitoring Year						
Month	**2013**	**2014**	**2015**	**2016**	**2017**	**Total**	**Percent**
July	1	0	0	0	0	1	0.4
August	5	0	3	4	11	23	8.7
September	8	20	14	18	10	70	26.6
October	15	22	23	28	11	99	37.6
November	10	14	15	3	0	42	16.0
December	0	8	3	0	2	13	4.9
January	10	0	0	0	0	10	3.8
February	4	0	0	0	0	4	1.5
March	1	0	0	0	0	1	0.4
total	54	64	58	53	34	263	100

Table A-3. Number of culverts by owner type measured per year for implementation monitoring.

Owner Type	Year 2013	2014	2015	2016	2017	Total	Percent
local government	25	22	20	24	17	108	41.1
state government	12	15	10	2	0	39	14.8
WSDOT	6	0	7	13	8	34	12.9
private	11	26	21	13	9	80	30.4
other*	0	1	0	1	0	2	0.8
total	54	64	58	53	34	263	100

* Two instances of "other" were the Natural Resources Conservation Service and the Chehalis Basin Fisheries Task Force.

Table A-4. HPA permit issuance years for each year of implementation monitoring. In parentheses are number of permits issued with new Hydraulic Code Rules that become effective on July 1, 2015.

Issuance Year	Monitoring Year 2013	2014	2015	2016	2017
2010	0	1	0	0	0
2011	0	0	0	0	0
2012	12	0	0	0	0
2013	41	29	6	0	0
2014	1	34	18	0	0
2015	--	--	34 (33)	25 (24)	(4)
2016	--	--	--	28 (26)	(11)
2017	--	--	--	--	(19)
total	54	64	58	53	34

Table A-5. Number of culverts by cross-sectional shape per year.

Culvert Shape	Year 2013	2014	2015	2016	2017	Total	Percent
Round (circular)	8	18	13	8	9	56	21.3
Elliptical	0	2	2	2	0	6	2.3
Squash	15	22	8	4	4	53	20.2
Box (rectangular)	16	11	18	25	12	82	31.2
Bottomless*	15	11	17	14	9	66	25.1
total	54	64	58	53	34	263	100

* Current conventions refer to "bottomless" culverts as "arched" culverts regardless of shape (i.e., rectangular or a true arch).

Table A-6. Results (number of culverts each year) of fish passage barrier assessment done for implementation monitoring. Numbers in parentheses indicate number of culverts that were partial fish passage barriers.

Assessment Level	Barrier?	2013	2014	2015	2016	2017	Total
		Year					
	No	48	47	51	45	29	220
A	Yes	1 (1)	4	0	2 (1)	0	7 (2)
	Unknown	0	1	2#	0	1#	4
	No	0*	9	2	3	3	17
B	Yes	0	1 (1)	3 (3)	0	0	4 (4)
	Unknown	5	2	0	3	1	11
	No	48	54	53	48	32	237
Overall	Yes	1 (1)	5 (1)	3 (3)	2 (1)	0	11 (6)
	Unknown	5	3	2	3	2	15
	Total	54	64	58	53	34	263

* No Level B assessments were done in 2013. Therefore, the status of culverts that required a Level B assessment is unknown.

One culvert was on a non-fish-bearing stream, and consequently, no fish passage barrier assessment was done for it.

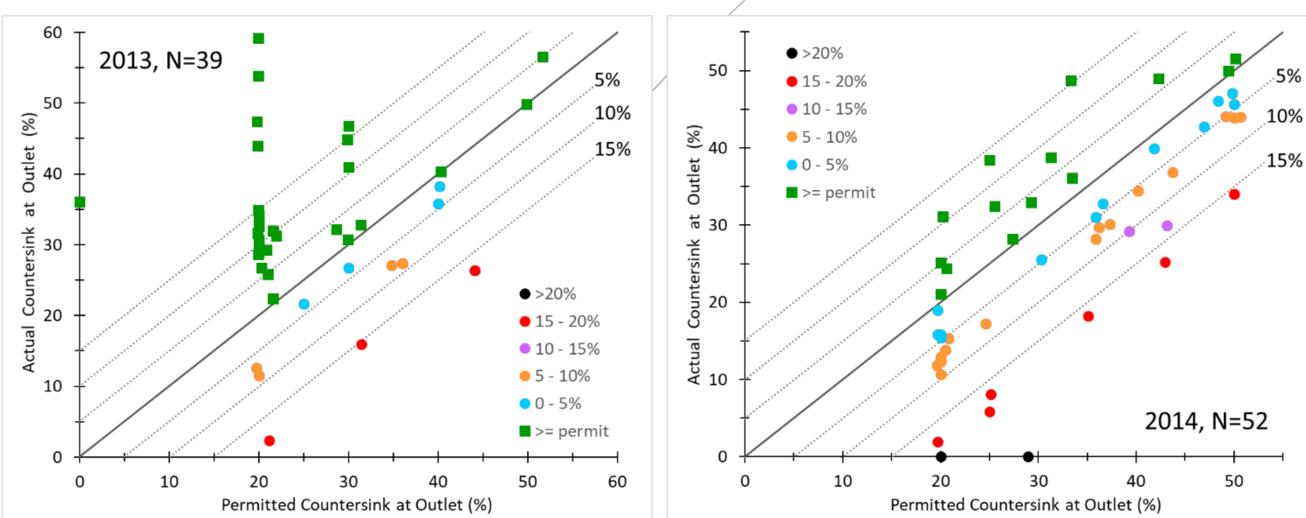


Figure A-1. Comparison of actual with permitted minimum culvert countersink at the outlet. Square, green markers (points) signify culverts that met permit specifications. Actual countersink equals permitted countersink on solid diagonal line, and dotted lines represent different levels of difference between actual and permitted countersink. N is the number of culverts that had a specification for culvert minimum countersink on its permit or on the project plans. Culvert countersink at outlet was measured differently in years 2013 and 2014. In 2013, countersink measurement method had a positive bias, and in 2014 the countersink measurement method had a negative bias.

Appendix B. Data Form for Culvert Implementation Monitoring

HPA Control Number ________________________

FPDSI Number _______________ ☐ New ☐ Existing

Permitting Biologist & Phone ____

HPA Issuance Date _____________________ Completion Date ______________________

Lat/Long ____

Applicant (or Landowner) Name & Phone ____

Road Name___________________________

Stream Name_______________________________ Trib To_______________________________

Owner______________________________ Phone__________________

Address____

Freshwater Culverts
Implementation Monitoring

Pre-Site Information

Water Crossing Structure Design

☐ no-slope ☐ stream-simulation ☐ hydraulic ☐ unknown

☐ other ________________________ where found ________________________

Culvert Shape

☐ RND ☐ ELL OX ☐ SQSH

☐ ARCH ☐ OTH ________________________

Culvert Material

☐ PCC ☐ CPC ☐ CST ☐ SST ☐ CAL ☐ SPS ☐ SPA ☐ PVC ☐ TMB

☐ MRY ☐ UNK ☐ OTH ________________________

Configuration

culvert span _________ culvert rise _________ culvert length _________ culvert slope _________

Culvert Bed

streambed slope (within culvert @ thalweg) _________

outlet countersunk depth _________ inlet countersunk depth __________

outlet invert elevation _________ inlet invert elevation _________

Number of Coarse Bands __________ Baffles __________

Culvert width at streambed

downstream _________ upstream _________

Channel width __________ ☐ BFW ☐ OHW ☐ OTH _________ where found _____________________

Other features described in permit or plans (e.g., armoring, grade controls, fishways, LWM, etc.) AND any comments:

____

____

____

On-site Information

Reviewer Name(s) ______________________________
Date of field review ____________________________
Lat/Long _______________________________________
Pic #s ____

HPA Control Number ______________________________
FPDSI Number ___________________ ☐ New ☐ Existing
Culvert Sequencer ___________
Barrier ☐ Yes ☐ No ☐ Unknown
Method ☐ Level A ☐ Level B
% Passibility ☐ 0 ☐ 33 ☐ 67 ☐ 100

Elevations: Benchmark located? ☐ Yes ☐ No

Benchmark elevation on **plans** / **site** __________ (Circle One) Benchmark elevation FS(-) _________ Instrument Height (IH)_________

Outlet **invert** / **soffit** elevation FS(-) __________ (Circle One) Inlet **invert** / **soffit** elevation FS(-) __________ (Circle One) IH_______________

Outlet thalweg elevation FS(-) __________ Inlet thalweg elevation FS(-) __________ IH_______________

Outlet Headroom __________ Inlet Headroom ___________

Elevations *For RND or ELL Pipes with an Uncentered Thalweg*

Inlet: Invert soffit elev FS(-) ____________ Thalweg soffit elev FS(-) ____________ Location _____________________

Outlet: Invert soffit elev FS(-) ____________ Thalweg soffit elev FS(-) ____________ Location _____________________

Culvert Shape

☐ RND ☐ ELL BOX ☐ SQSH

☐ ARCH ☐ OTH ______________________________

Culvert Material

☐ PCC ☐ CPC ☐ CST ☐ SST ☐ CAL ☐ SPS ☐ SPA ☐ PVC ☐ TMB

☐ MRY ☐ UNK ☐ OTH ______________________________

Configuration

culvert span ___________ culvert rise ___________ culvert length ___________ culvert slope ___________

Culvert Width at Streambed: outlet ___________ inlet ___________

Culvert Bed: Level A Countersunk ☐ Yes ☐ No Bed elevation line present? ☐ Yes ☐ No

Thalweg Established at construction? ☐ Yes ☐ No Streambed slope (within culvert @ thalweg) ___________

WDIC ___________ **Backwatered** ☐ Yes ☐ No **Apron** ☐ Yes ☐ No **Tide Gate** ☐ Yes ☐ No **Road Fill** ___________

Number of Coarse Bands ______ **# of Baffles** ______ **Baffle Type** ________ **Hydro Drop** __________ **Drop Location** _______

Plunge Pool ☐ Yes ☐ No Length _______________ Average Depth ________________ Scour Width ________________

Upstream Bankfull Width _______________ Upstream Bankfull Depth ______________

Upstream Bankfull Width _______________ Upstream Bankfull Depth ______________

Downstream Bankfull Width _____________ Downstream Bankfull Depth ______________

Downstream Bankfull Width _____________ Downstream Bankfull Depth ______________ Avg BFW _____________

Stream slope downstream of culvert ___________ **Stream slope upstream of culvert** ___________

Other Features and Comments:

____

Appendix C. Miscellaneous Data Summaries for Implementation Monitoring of Marine Shoreline Armor

Table C-1. Summary of implementation monitoring project counts by monitoring year.

	Monitoring year			
	2014	**2015**	**2016**	**Total**
Survey window	01/2009 - 09/2014	10/2014 - 09/2015	10/2015 - 09/2016	
Permit source	HPMS	APPS	APPS	
Initial count	134	226	128	488
Applicable pool *	48	119	107	274
Insufficient project information: count (%) †	6 (12.5)	5 (4.2)	12 (11.2)	23
Field surveyed	31	11	27	69

* Standard only (i.e., not emergency) HPA-permitted projects for new, extension and replacement marine shoreline hard armor where construction has been completed.
† HPA-permitted projects unsuitable for implementation monitoring due to lack of measureable information to assess consistency of structure location and length (box 3-2).

Table C-2. Count of marine shoreline hard armor projects measured for implementation quality by county.

	Project type			
County	**New**	**Extension**	**Replacement**	**Total**
Clallam	1	0	0	1
Island	2	1	6	9
King	0	0	4	4
Kitsap	5	0	19	24
Mason	4	2	1	7
Pacific	0	1	2	3
Pierce	1	0	4	5
San Juan	7	2	2	11
Skagit	2	1	1	4
Thurston	0	0	1	1
Total	22	7	40	69

Table C-3. Count of projects by HPA permitted versus MSDG recommended armor design technique.

	MSDG recommended design			
HPA permitted design	**Natural**	**Soft**	**Hard**	**Total**
Soft	5	2	4	11
Hard	54	26	67	147
Total	59	28	71	158

Table C-4. Count of projects by HPA permitted versus MSDG recommended armor design technique by site risk category.

HPA Permitted Design	MSDG recommended design							
	Low risk	Moderate risk			High risk			
	Natural	Natural	Soft	Hard	Natural	Soft	Hard	Total
Soft	4	1	2	4	0	0	0	11
Hard	50	4	26	63	0	0	4	147
Total	54	5	28	67	0	0	4	158

Table C-5. Count of projects reviewed by risk category per each monitoring year and project type.

		Risk Category			
		High	Moderate	Low	Total
Monitoring year	2014	1	46	38	85
	2015	0	33	11	44
	2016	3	21	5	29
	Total	4	100	54	158
Project type	New	2	28	14	44
	Extension	0	8	5	13
	Replacement	2	64	35	101
	Total	4	100	54	158

Table C-6. Count of new projects that describe location of armoring structure relative to ordinary high water (OHW). OHW is used in Hydraulic Code Rules to specify allowed shoreline armor locations (WAC 220-660-370). "Information source" denotes from where OHW information was found, "location description" denotes type of measurement relative to OHW, and "measureable" denotes whether OHW location could be measured in field given the quality of description in permit or application materials. Parentheses indicate number of permits for which location could be measured from project plans.

		Monitoring Year			
		2014	**2015**	**2016**	**Total**
Information source	HPA Permit	1	0	1	2
	Application material	6	2	5	13
	Not provided	5 (2)	1	1	7 (2)
	Total	12	3	7	22
Location description	Distance	6	1	5	12
	Elevation	3	1	1	5
	Not obtainable	3	1	1	5
	Total	12	3	7	22
Measurable	Yes	3	1	2	6
	No	6	1	4	11
	Not obtainable	3	1	1	5
	Total	12	3	7	22

Table C-7. Count of extension and replacement projects by source of structure location information. Location was expressed relative to existing shoreline armor.

	Monitoring Year			
Information Source	**2014**	**2015**	**2016**	**Total**
Permit	17	7	10	34
Application material	2	1	10	13
Total	19	8	20	47

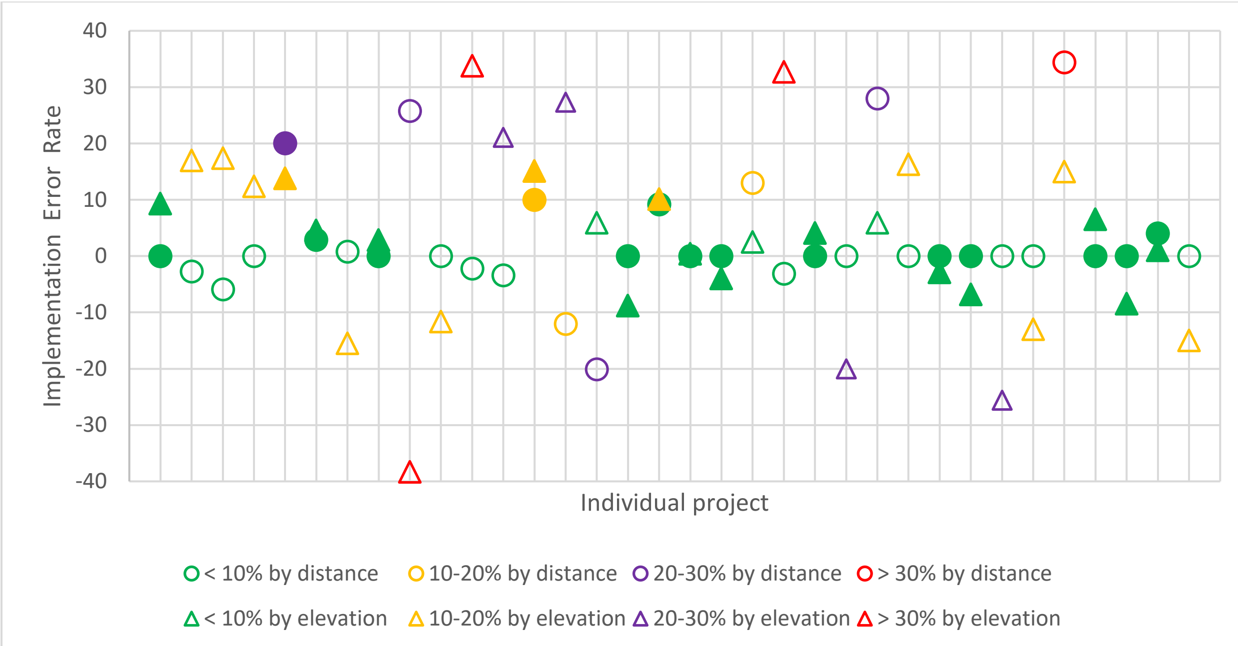


Figure C-1. A comparison of permitted structure location provided as known elevation and horizontal distance for shoreline armor in 2014, 2015 and 2016. Each vertical line represents an individual project (n=34) with implementation errors for location by both elevation (triangle) and by distance (circle), where filled shapes represent implementation errors within 10% of each other.

Appendix D. Data Forms for Implementation Monitoring of Marine Shoreline Armor

Form for information collected from HPA permit:

HPA Number__________________ APP ID__________ Habitat Biologist__________________

Landowner Info ____

Agent Info ____

Permit Dates ____

Project Location (address, coordinates, parcel) ______________________________

Project Name ____

Project Type ☐ New ☐ Extension ☐ Replacement ☐ Repair ☐Removal ☐ Other__________________

Armor Type ☐ Hard Protection ☐ Soft Protection ☐ Mixed ☐ Unknown ☐ Other __________________

Armor Design ☐ Vertical Wall ☐ Revetment ☐ Hardened Toe ☐ Biotechnical ☐ Other __________________

Armor Material

☐ Riprap (rock) ☐ Concrete Bags/Blocks/Forms ☐ Solid Concrete ☐ Metal ☐ Wood Vertical/ Horizontal ☐ LWD

☐ Sheet Pile ☐ Gabions ☐ Bio bags ☐ Geotextile ☐ Other ______________________________

Armor Construction Specifications

Location of dimension (LOD): 1 – HPA permit, 2 – supporting document, 3 – measured from supporting document, 4 – not provided

Benchmark Description____LOD________

Armor Length ____________ LOD ___ Armor Height ________LOD___ Armor Width ________ Parcel Width________

Armor Location (elevation)____LOD________

Armor Location (distance)____LOD________

Ordinary High Water Mark ____LOD________

Armor tied into adjacent armoring? *(looking landward)* Left: ☐ Yes ☐ No ☐ NA ☐NP Right: ☐ Yes ☐ No ☐ NA ☐NP

Return Walls ☐ Left ☐ Right ☐ NA ☐ NP If present: ☐Cornered (90°) ☐Curved/Angular (___°)

General Permit Provisions

☐ Allow Access ☐ Construction Notification ☐ Provide Photos ☐ Establish Benchmark ☐ Other __________________

Fish Protection Provisions

☐Shellfish ☐Surf Smelt ☐ Sand Lance ☐ Herring ☐ Salmon ☐ Other______________________________

Work Window Specified (Dates/Times):____

Forage fish surveys conducted? ☐ Yes ☐ No If so, spawning document in: ☐Surf Smelt ☐ Sand Lance ☐ Herring

Habitat Protection Provisions

☐ Fill Depressions ☐ Remove Waste ☐ Minimize Upland Vegetation Removal ☐Protect Intertidal/Marine Vegetation

☐ Incorporate Drainage ☐ Re-Vegetate Post Construction ☐ Retain Habitat Features ☐ Beach Nourishment

Site Information Nearest Tide Station____

Shore Form Type: ☐ Feeder Bluff ☐ Transport Zone ☐ Modified ☐ Accretion ☐ Other__________________

Drift Direction: ☐ Left to Right ☐ Right to Left ☐ Divergent ☐ No Appreciable Drift ☐ Undefined

Beach Alignment: ☐ Swash (waves parallel to beach) ☐ Drift (waves oblique to beach)

Setback Distance [bluff crest (or OHW) to ww-most infrastructure] ______________________________

Fetch Distance (max S or max/2 N, E, W quadrant)______________________________

Backshore Width (distance MHHW to upper beach)______________________________

1 of 2

Form for information collected during site visit:

HPA Control Number____________________ ☐ New ☐ Existing
Parcel Number ____________________
Landowner/Applicant Name ____________________
Landowner/Applicant Phone ____________________

Implementation Monitoring

Post-construction

Reviewer Name(s) ____________________ Last High Tide (St) ____________________
Date/Time of Site Survey____________________ Time ____________ Elevation____________
Lat/Long ____________________ Nearest Harmonic (St)____________________

Project Type

☐ New Armor ☐ Armor Extension ☐ Replacement ☐ Repair ☐Removal ☐ Other____________________

Armor Type

☐ Hard Protection ☐ Soft Protection ☐ Mixed ☐ Unknown ☐ Other ____________________

Armor Design

☐ Vertical Wall ☐ Revetment ☐ Hardened Toe ☐ Biotechnical ☐ Unknown ☐ Other ____________________

Armor Material

☐ Riprap (rock) ☐ Concrete Bags/Blocks/Forms ☐ Solid Concrete ☐ Metal ☐ Wood Vertical/ Horizontal ☐ LWD
☐ Gabions ☐ Bio bags ☐Sheet Pile ☐ Other ____________________

Armor Construction Specifications

Reference Mark Located ☐ Yes ☐ No ☐ NP ____________________
Armor Length ____________ Armor Height ____________ Armor Width ____________ Parcel Width____________
Armor Elevation at Toe____________________
Armor tied into adjacent armoring? (*facing landward*) Left side: ☐ Yes ☐ No ☐ NA Right side: ☐ Yes ☐ No ☐ NA
Return Walls ☐ Present ☐ Absent If present: ☐Cornered (~90°) ☐Curved/Angular
Drainage tight lines visible: ☐ Yes ☐ No

Beach Observations

Sediment scour: ☐ Yes ☐ No If present: ☐ left of armor ☐ forward of armor ☐ right of armor
Sediment accumulation: ☐ Yes ☐ No If present: ☐ left of armor ☐ forward of armor ☐ right of armor
Evidence of nourishment: ☐ Yes ☐ No Habitat features retained: ☐ Yes ☐ No
Depressions filled: ☐ Yes ☐ No Waste removed: ☐ Yes ☐ No

Backshore Observations

Vegetation removal minimized: ☐ Yes ☐ No ____________________
Re-vegetation effort evident: ☐ Yes ☐ No ____________________

1 of 2

See back for additional comments/notes

Form for applying marine shorelines design guidelines (MSDG):

Shore Type (ST) Determination	Score
No Appreciable Drift (NAD) - Bedrock/Low Energy	0
Modified, Accretion, NAD - Delta	1
NAD - Artificial, Transport Zone, Pocket Beach	2
Feeder Bluff	3
Feeder Bluff Exceptional	4

Fetch (F) Determination		
Fetch (miles)	Score	Wave Energy
0-1	1	Low
>1-5	2	Medium
>5-15	3	High
>15	4	Very High

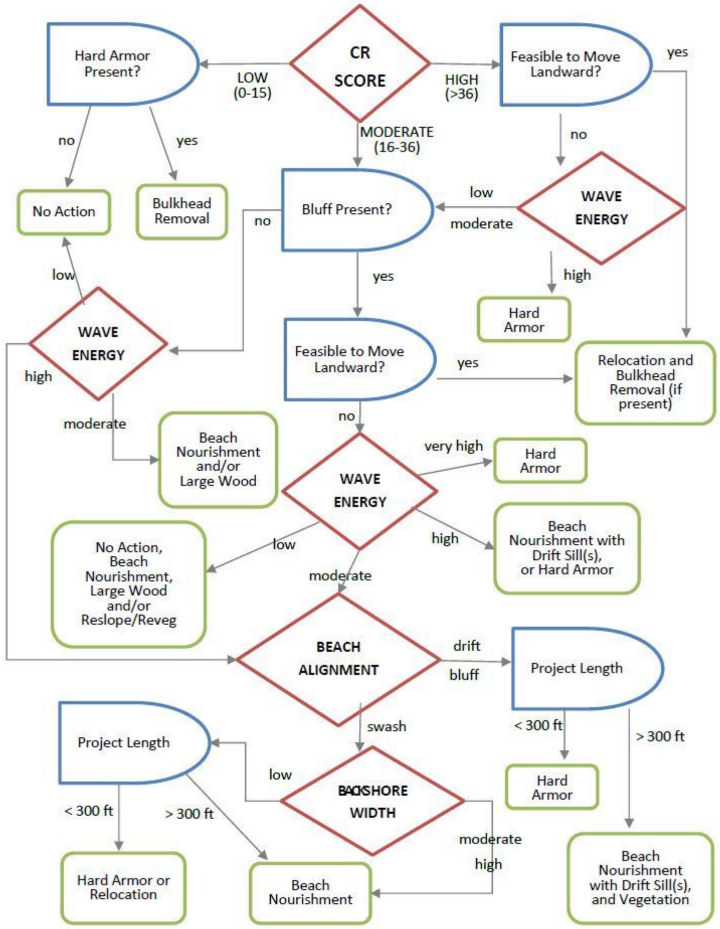
Setback (SB) Determination	
Distance	Score
>60 ft	1
36-60 ft	2
21-35 ft	3
0-20 ft	4

Infrastructure (I) Type	Score
Property without structures	1
Septic or unattached residential structure, not lived in	2
Home or residential building	3
Major infrastructure	4

Score Totals
ST (_____) + F (_____) = Erosion Potential, **EP** (_____)
SB (_____) + I (_____) = Infrastructure Threat, **IT** (_____)
EP (_____) + IT (_____) = Cumulative Risk, **CR** (_____)

Backshore Width	Wave Energy Categories		
	LOW	MOD	HIGH
0-5 ft	Low	Low	
5-10 ft	Moderate	Low	
10-15 ft	High	Low	
15-20 ft		Moderate	Low
20-25 ft		Moderate	Low
25-30 ft		High	Moderate
30-35 ft		High	Moderate
35+ feet			High

See back for comments



Appendix E. Implementation Evaluation for Effectiveness Monitoring

Pre-site information from HPA permit and construction plans

Water Crossing Structure Design

☐ no-slope ☐ stream-simulation ☐ hydraulic ☐ unknown

On-site Information from channel and culvert measurements

Mean bankfull width (m) ______________

channel slope outside culvert (%): downstream ________________ upstream _______________

culvert slope (%) ____________________ (Use bed slope for arch culverts)

culvert width at streambed (m): outlet _________________ inlet ________________

countersunk depth (difference in thalweg bed elevation and culvert invert elevation) (m):

outlet ________________ inlet ________________

culvert rise (m) ________________

calculate % countersunk: outlet ______________ inlet ______________

No-Slope Culvert Evaluation	**Stream Simulation Culvert Evaluation**
1) ☐ maximum upstream and downstream channel slope < 3%	**X** = (1.2 *BFW + 0.61) *0.95 = ______________________________
2) ☐ |culvert slope| < 2%	**Y** = 1.25 * upstream slope *1.05= ______________________________
3) ☐ culvert width at streambed (inlet or outlet) * 1.05 ≥ BFW	1) ☐ culvert width at streambed (inlet or outlet) ≥ **X**
	2) ☐ culvert slope ≤ **Y**
If culvert is NOT bottomless, then:	If culvert is NOT bottomless, then:
4) ☐ % countersink at outlet * 1.05 ≥ 20%	3) ☐ 30% ≤ % countersink at outlet * 1.05 % countersink at outlet * 0.95 ≤ 50%
5) ☐ % countersink at inlet * 0.95 ≤ 40%	4) ☐ 30% ≤ % countersink at inlet * 1.05 % countersink at inlet * 0.95 ≤ 50%

Note: No-Slope and Steam Simulation must meet all above criteria to do effectiveness monitoring.

Hydraulic Design Culvert Evaluation

If HPA or plans indicate the culvert is based on hydraulic design, then evaluate culvert with Level A and if needed proceed to a Level B Fish Passage Barrier Assessments. If culvert is 100% passable, then do effectiveness monitoring.

Unknown Culvert Design

If culvert design is unknown and it fails the no-slope and stream-simulation evaluations above, then no effectiveness monitoring. If it passes either then categorize accordingly as a no-slope or stream-simulation, then do effectiveness monitoring. If it passes both then categorize as a stream-simulation.

Appendix F. HPA Culvert Effectiveness Monitoring Field Protocol

Step by Step Directions for Year 1 Data Collection

1. Set up primary benchmark.
   - Benchmark should be placed on a sound flat area outside of both the creek and the road prism where it is likely to be undisturbed for the next ~50 years
   - Use a fence post driver to bury a T-post until approximately ~1 foot remains above ground
   - Take pictures of the benchmark with identifying nearby landmarks for reference in future years
   - Primary benchmark (BM1) elevation is set to 100, take a backsight to BM1 to determine instrument height (IH1).

2. Set up secondary benchmark.
   - Use hammer and nail to establish a secondary benchmark within clear sight of the primary benchmark, usually a tree in the vicinity that is also outside of the creek and the road prism.
   - If a hammer and nail aren't available it is possible to use the structure itself (such as the top of the headwall) as a secondary benchmark. It is important in this case to mark with spray paint and take several pictures of where the elevation was taken on the structure as the spray paint will likely fade
   - Determine secondary benchmark (BM2) elevation relative to the primary benchmark.

3. Determine longitudinal transect length.
   - The transect should be 30x bankfull width (BFW). BFW is usually available from implementation monitoring data, however, if it is not, measure BFW u/s and d/s following WDFW BFW estimation guidelines.

4. Determine the culvert length. This information is also typically available from implementation monitoring data, however, if it is not, measure the culvert length per WDFW measurement protocol (*http://wdfw.wa.gov/publications/00061/*)
   - The length of the culvert is considered part of the total length of the 30X BFW longitudinal transect. Subtract the culvert length from the transect length (30x BFW) and divide the remaining number by 2. This is the distance upstream from the inlet and downstream from the outlet that the longitudinal profile will be measured.

5. Adjust the longitudinal transect length in the case of long culverts.

   \- Periodically you will encounter culverts which occupy a large percentage of the total longitudinal transect length.

   \- When a culvert length is equal to, or greater, than 1/3 of the total longitudinal transect length, it will be necessary to adjust the upstream and downstream long transect lengths. For example, if the total longitudinal transect length of a site is 30 meters, but the culvert is ≥ 10 m long, it will be necessary to adjust the length of the upstream and downstream long transects.

- To compensate, make the length of the upstream and downstream long transects greater than the length of the culvert. For example, if the culvert from the previous example was 15 m, your upstream and downstream longitudinal transects should be at >15 m long.
- In other words the sum of the upstream and downstream long transect lengths should be greater than 2/3 of the total longitudinal transect length.

6. Set up the upstream longitudinal transect and upstream cross-section stations.
   - Place a stake in the thalweg at the inlet of the pipe.
   - Extend the measurement tape along the thalweg for the distance determined above for the upstream longitudinal transect ([30X BFW – Culvert Length] / 2). Stake the tape as necessary in the channel to keep it aligned as closely as possible to the thalweg.
   - This tape will determine the stationing for the upstream cross-sections.

7. Determine spacing for upstream cross-sections.

   - A total of 4 cross-sections will be measured upstream, including one cross-section directly at the inlet of the pipe (4 will also be measured downstream) of the culvert.
   - Space the cross-sections ~2-3x BFWs apart (round to the nearest half digit) depending on stream topography.
   - When wingwalls are present at the inlet of the culvert place a transect directly at the inlet, and another transect at the end of the wingwall. When there is only one wingwall, or two wingwalls of different length, place the second transect at the end of the furthest extending wingwall. The same protocol applies to downstream wingwalls.
   - If aprons are present (unlikely) the end of the apron is considered the end of the culvert.

> **Site Example:**
> BFW: **2.75m**
> Pipe length: **19.4m**
>
> Longitudinal transect length: **82.5m**
> Longitudinal transect w/o pipe: **63.1 m**
> U/s longitudinal transect length: **31.5m**
> Cross-section spacing: **0, 5.5, 11, 16.5m**

8. Set up and measure the farthest upstream cross-section.
   - Extend the tape perpendicular to the channel between the left and right top of bank, staking it where the water depth is usually zero.
   - TAKE PHOTOS OF THE CROSS-SECTION. This is the primary mechanism for determining where the cross-sections are located for subsequent years. Ensure that the photos capture the end points and other defining features.
   - Take the first elevation at the Top of Left Bank (Station "0"), as well as water depth, and substrate. At times the top of bank and bankfull width measurements may be the same.
   - **At the top of bank, and each subsequent station, record the station number along the cross-section, elevation foresight (FS-), water depth, and substrate type.**

- Next take measurements at the left bank BFW elevation. Because streambeds have often been disturbed during the course of construction, the point at which water begins to overflow into the floodplain is very unclear. Measuring the BFW in these situations requires some professional judgement and extrapolation from undisturbed BFWs.
- Next take a measurement at mid-bank elevation between the top and the toe of the bank to capture the bank angle. There will be situations where the mid-channel elevation is not available, such as on a vertical bank or undercut, which means that the BF and toe cross section stations are the same. In that situation it is permissible to not take a mid-bank elevation measurement – *but only in that situation*. If there are undercut banks below bankfull, it is very important to take elevation measurements at the top of the undercut (which would be recorded as the mid-bank elevation) and the toe. When there are undercut banks, measure how deep the undercut is into the bank (in other words – not water depth, but the depth of the lateral cut into the bank)
- Take a *minimum* of five bed measurements capturing the high and low channel bed elevations at relatively evenly spaced locations. Similar to the longitudinal profile measurements, channels with more variable bed morphology should be measured at a shorter interval, and with a greater number of stations, than channel beds with less variability.
- Following the same instructions as the left bank, take measurements at the right bank toe, mid-bank, bankfull, and top of bank.

9. Working downstream, measure the next three cross-sections with the final upstream cross-section at the culvert inlet (Station "0" on the long profile tape).
- Follow the guidance for step 7 for the remaining cross-sections.

10. Note large woody debris (LWD) on the datasheet at each transect.
- Count any LWD intersecting, or between cross-sections, within the bankfull channel. Wood pieces greater than 1 m long *and* greater than 30 cm in diameter will be counted as LW. Count each piece only once, even if the same piece crosses multiple cross-sections
- Be specific in noting where the wood is located. For example, "1 piece between cross-sections 2 and 3".

11. Measure upstream longitudinal transect.
- Starting at the upstream end of the transect, record the thalweg foreshot, noting the station as well as the water depth.
- If, such as in the callout example, the longitudinal transect length is 31.5 m the first station will be "31.50". Be sure to note on the data sheet the direction of profile stationing in the space provided ("US End of Transect →Inlet ○" or "US End of Transect ← Inlet ○"), as well as the station number at the furthest upstream end of the transect, and the inlet of the pipe. For example: You set up your 31.5 m long profile by running the tape starting from the inlet thalweg moving upstream. Then you start measuring stations and elevations at the

upstream most point, working your way back toward the pipe inlet. The "Direction of Profile" section on the worksheet should look like:

_31.5_ US End of Transect →Inlet ⊗ _0__

- Moving downstream, elevation foresights, station numbers, and water depths should be recorded at riffle crests (the location in a riffle with the highest elevation), at the lowest pool elevations, and at the tail-out of pools.
- A total 40-100 measurements are expected along the long profile (including within the culvert). Channels with more variable bed morphology should be measured at shorter intervals, with greater numbers of profile stations, than channel beds with less variability.
- Continue until station 0 is measured at the culvert inlet thalweg. (Note: The zero station measurement can be referenced back to the cross-section thalweg elevation at the inlet, or the within-culvert long profile, to double-check the precision of the measurements.)

12. Determine backwater elevation.
- While upstream of the structure, on or within one BFW of the structure, record the elevation of the highest observable water line.

NOTE: If possible, before moving the instrument to measure downstream elevations, measure back to the benchmarks as an additional check of the instrument height. If, during the course of taking the downstream measurements, errors are introduced, you will at least know that the upstream elevations are correct, and do not need to be remeasured.

13. Assess whether or not to proceed with the longitudinal profile through the culvert or begin the downstream long transect measurements.
- If the rotating laser level is in a position where it will not need to be moved to conduct the downstream survey, such as on the road with a good view upstream and downstream, begin the downstream survey (it is best to minimize the number of times that the instrument is moved).
- In some instances the dimensions and slope of the culvert and culvert bed will allow foresights to be taken through the length of the pipe. Determine whether turning points will be feasible to capture all eleven shots (see Step 14 below), or whether it is unfeasible/unsafe to capture the measurements within the pipe.
- If the instrument needs to be moved, such as if there was a turning point during the upstream surveying, and safety and dimensions permit, begin with the longitudinal profile through the culvert.

14. Set up and measure the culvert longitudinal profile.
- Extend and stake the measurement tape *straight* from the culvert inlet to the outlet (**not following the thalweg and not including culvert wingwalls**).

- At eleven evenly spaced stations through the culvert record the foresight, water depth, and substrate in the thalweg, as well as the substrate at the left and right bank toe. Long profile stations within the culvert can be rounded to whole numbers, except for the final station which should be taken directly at the outlet. Tip: Divide the length of the culvert by 10 to calculate the length between stations through the pipe.
- Following the example in the callout, spacing would be every 2 m starting at 0 m, and ending at the culvert outlet (19.4 m).

> Remember: For the upstream and downstream long profiles follow the thalweg with the transect tape. For the long profile through the culvert, stretch the tape straight through the culvert, *not* following the thalweg.

15. Set up longitudinal profile and downstream cross-section stations.
- Place a stake in the thalweg of the culvert invert at the downstream end.
- Pull the tape along the thalweg for the distance determined above for the longitudinal profile. Stake the tape as necessary in the channel to keep it aligned as much as possible with the thalweg.
- This tape will determine the stationing for the downstream cross-sections.

16. Determine spacing for downstream cross-sections.
- Refer to Step 5

17. Set up and measure downstream cross-sections.
- Follow Steps 6 and 7 beginning the first downstream cross-section at the culvert outlet.

18. Measure downstream longitudinal profile.
- Starting at the downstream end of the transect, record elevation of thalweg, noting the station as well as the water depth.
- Be sure to note on the data sheet the direction of profile in the space provided. This is particularly important at the downstream end since the stationing will likely have to be changed to integrate it with the upstream profiles.

19. Close the loop.
- Refer back to the benchmark to ensure that there are no changes to the instrument height. This may require employing additional turning points until the instrument can be moved to a point where it can measure back to the benchmark.
- The maximum allowable error is 0.03 m. If the error is greater than 3 centimeters it may be possible to determine where the error was introduced by comparing elevations the same stations on the long profile and cross sections. Anything measured after the error was introduced will have to be re-measured.

Year 2, 5, 10… etc. Data Collection

1. Confirm elevations of the primary and secondary benchmarks.
   - Set the rotary laser in a location where you can see the primary and secondary benchmarks.
   - Measure the instrument height based on the primary benchmark.
   - Measure the elevation of the secondary benchmark.
   - Refer back to the first year effectiveness data, and confirm that the primary and secondary benchmark elevations are the same (± 1 cm).
   - If the elevations are different from year 1, first try remeasuring the elevations. Secondly, refer back to the photos that were taken during the first year. Try to determine which benchmark may have been disturbed or moved in the interim.
   - Reestablish the benchmark elevations based on the benchmark that was undisturbed. For example, if the primary benchmark was disturbed between years 1 and 2, recalculate the new primary benchmark elevation based on the secondary benchmark.
   - If you have high visibility spray paint, freshen the paint on the benchmarks.
2. Measure longitudinal profile elevations upstream and downstream.
   - The longitudinal profile transect should be the same length as the first year, and continue to follow the thalweg.
   - Measure long profile elevations using the same methods as the first year, capturing the contours of the stream.
   - *Note: It is likely that the thalweg has moved between the first year, and subsequent visits. It is more important to follow the new thalweg than to try to place the tape in the same location as the first year.*
3. Measure longitudinal profile through the culvert.
   - The longitudinal profile transect should be stretched straight through the culvert.
   - Measure culvert long profile elevations at the same stations as the first year.
4. Measure cross-sections elevations.
   - Using the pictures taken during the first year, or subsequent visits, place the cross-section transects at the same locations as the first year, paying particularly close attention to the top of bank stations.
   - Measure cross-section elevations using the same methods as the first year, capturing the contours of the cross-section.
   - Take new photographs of the cross-section transect, making sure to capture the locations of the top of bank stations, as well as a representative photo of the transect location.
5. Backwater elevation, BFW and passability.
   - Immediately upstream of the structure, look for the highest backwater elevation. This should be more obvious in the second year. Look for staining on the inside of the structure, or the highest scour line immediately upstream.
   - Measure a representative bankfull width.
   - Confirm that the structure is still passable to fish. Typically this is as easy as comparing span to BFW, and confirming that the structure is still countersunk. Perform a Level B if necessary.

SPECIAL CASES:

You will often encounter situations in the field that complicate the effectiveness protocol. In those situations it is typically best to call your supervisor for guidance. What follows are instructions for special cases that we regularly encounter in the field:

Multiple replaced culverts in a line – Successional replaced culverts should be measured in such a way that they reference the same benchmark elevations, and have a continuous longitudinal profile throughout.

Older non-replaced culverts - Long-profiles and cross-sections will end at the entrance to older non-replaced culverts.

Upstream or Downstream Confluence/Braiding – Follow the channel that appears to have the greatest flow. If, on the downstream longitudinal transect, you encounter a much larger river or stream that contributes much greater flow, then it is permissible to stop the long transect at the confluence with the larger stream.

Substrates:

Size Class	Code	Size Range (mm)	Description
bedrock; smooth	BS	> 4,000	larger than a car
bedrock; rough	BR	> 4,000	larger than a car
boulder	BL	250 - 4,000	basketball to car
cobble	CB	64 - 250	Tennis ball to basketball
coarse gravel	GC	16 - 64	marble to tennis ball
fine gravel	GF	2 - 16	ladybug to marble
sand	SA	0.06 - 2	gritty to ladybug
silt/clay/muck	FN	< 0.06	not gritty
hardpan	HP		firm consolidated fine
vegetated organic	VO		any size
wood	WD		any size
Rip-rap	RR		any size
other	OT		

In cases where vegetated organic material covers a substrate item which creates a large jump in bed elevation, such as moss growing on a boulder in the middle of a river, please record both substrates so that it obvious why there is the difference in bed material, and that the jump is high enough that it is over the scour elevation. State the primary substrate first, followed by the organic material (E.g. BL-VO).