Anadromous Fish Floor Spatial Analysis

Findings Report

Prepared for

The Water Typing Rule Committee of the Washington State Forest Practices Board

By

Anadromous Fish Floor Project Team

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Executive Summary

Introduction

This report presents the findings of the Anadromous Fish Floor Workgroup. The Workgroup was established in response to a request by Washington's Forest Practices Board for stakeholders engaged in the state's forest practices adaptive management program to collaboratively analyze and evaluate physical stream characteristics downstream from which all streams can be presumed to have anadromous fish use. The 'anadromous fish floor' (AFF) in the permanent forest practices water typing rule would establish the location where protocol fish surveys to determine water type may begin under the Fish Habitat Assessment Methodology (being developed concurrently), thereby reducing electrofishing in waters that are presumed to have anadromous fish use.

The tasks of the workgroup included compiling currently available data on locations of known and presumed fish use from multiple western Washington watersheds and assessing those locations against modeled channel attribute metrics, along with an assessment of the performance of these metrics. Metrics evaluated included channel gradient, changes in channel gradient, channel width, changes in channel width, and vertical and non-vertical anadromous fish migration barriers and obstacles. The Forest Practices Board (FPB) charged the workgroup with developing recommendations on potential future field studies, as needed, to address technical uncertainties. The AFF project team focused on conducting the analyses to compare the AFF alternatives; the balance of risk between underestimating known anadromous stream length and overshooting the fish-non-fish habitat break point locations is the subject of the associated policy report.

Workgroup Organization

Membership of the Project Team and Workgroup included representatives from tribal, state, landowner and conservation stakeholders. Dan Miller, Kevin Andras and Lee Benda from TerrainWorks were responsible for the GIS modelling and mapping and supported the project team throughout the process of interpreting and summarizing the results.

A Charter was developed and approved by the FPB that outlines the problem to be addressed by the workgroup, and roles and responsibilities of the workgroup members:

> **AFF Charter:**
>
> ***Problem Statement***
>
> The Board Committee recognizes that additional data and analysis on physical stream metrics and the distribution patterns of anadromous and other fish species will inform the development of anadromous fish floor recommendation(s).
>
> The Board Committee requests stakeholders gather and analyze data to help evaluate appropriate physical criteria that can define an anadromous fish floor. The workgroup will gather and analyze data on physical stream characteristics and anadromous fish habitat distributions, and, to the extent possible, make consensus recommendations on the anadromous fish floor.

Workgroup Roles and Responsibilities

Water Typing Board Committee:

- Provide guidance and oversight to the workgroup
- Facilitate discussions with the entire Board and facilitate delivery of a final anadromous fish floor recommendations or minority/majority report

Project Manager:

- Organize meetings, set meeting agendas, take notes, and maintain open and timely communication between all members of the workgroup and Board Committee.

Principal Investigators:

- Perform technical analyses and lead in drafting technical report with QA/QC to assure data quality.
- Develop methods for analyzing and describing the relationship between physical stream characteristics and anadromous fish habitat.
- Communicate and collaborate as necessary with technical workgroup members to complete the analyses in the given timeframe.
- Communicate to the workgroup what specific technical questions will be answered in the analyses and what information will result from the analyses.

Caucus Members: (Membership is open to all adaptive management stakeholder participants)

- Provide input, guidance and feedback to Principal Investigators and assist them as requested (and time allows) to complete tasks
- Assist in the drafting of technical report and recommendations based on data and analyses generated by Principal Investigators.

Key Findings

- The total lengths of stream channels covered by each AFF alternative varied in predictable ways. Alternatives that used the highest gradient thresholds (10%) to terminate the AFF tended to extend farthest upstream; alternatives that used lower gradient thresholds (7% and 5%) tended to end the AFF lower in watersheds.
- The alternative that did not use a gradient threshold but instead incorporated known and presumed anadromous data and extensions based on a lack of gradient changes or obstacles at tributary junctions had the shortest overall AFF length.

Relation of the AFF alternatives to Anadromy

- Alternatives that used a 10% gradient threshold tended to encompass a higher percentage of anadromous fish data and extend a greater distance upstream of those points than alternatives that used lower gradient thresholds (e.g. 5%) or that used a 5% change in gradient.
- Alternatives that used lower gradient thresholds or that used a 5% change in gradient tended to fall short of the anadromous points more often and by greater distances than alternatives that used larger gradient thresholds.
- Many of the overall observed anadromous fish data points were located in low gradient streams (<2% gradient). ~90% of the anadromous data points had downstream sustained gradients of

10% or less. ~60% of the anadromous data points had downstream sustained gradients of 5% or less.

Relation of the AFF alternatives to concurred F/N Breaks

- All of the AFF alternatives extended above some proportion of the F/N break point locations.
- Alternatives that used a 10% gradient threshold tended to extend beyond F/N break point locations more often and over greater distances than those that used lower gradient thresholds or changes in gradient.
- Alternatives that used lower gradient thresholds or changes in gradient tended to fall short of F/N break points more often and by greater distances.

Relations of the AFF alternatives to barriers

- The inclusion of natural barriers as AFF termination points reduced the overall lengths of the AFF when compared to similar alternatives that relied solely on gradient thresholds.

Sustained gradients downstream from observed and presumed fish data

- 63% of the anadromous occurrence points have a maximum downstream gradient of 5% or less; 75% have maximum downstream gradient values of 7% or less; and 88% have maximum downstream gradient values of 10% or less.
- 28% of the F/N occurrence points have a maximum downstream gradient of 5% or less; 60% have maximum downstream gradient values of 7% or less; and 68% have maximum downstream gradient values of 10% or less.

Technical Recommendations

Adopt Alternatives A3 and A4 as AFF alternatives for consideration along with the previously-approved alternatives. The workgroup recognized that implementation of Alternative A could be greatly facilitated if its stopping criteria (10% sustained gradient or permanent natural barrier) are identified upstream from known anadromy, e.g. as represented in SWIFD, instead of from saltwater. This approach, analyzed as A3 and A4, also enables a more meaningful comparison of performance between Alternatives A and D.

Background

The Anadromous Fish Floor Proposals

Timber-Fish-Wildlife participants submitted proposals for an anadromous fish floor to be included as part of the permanent water typing system in February, 2018. The Board directed staff to form a technical workgroup to analyze available and current anadromous and resident fish distribution data and stream characteristics that would assist the Board in making a final determination of which anadromous fish floor criteria to adopt when finalizing the Forest Practices water typing system. A total of four AFF alternatives were approved by the Board for evaluation by the workgroup (Table 1).

Table 1. Anadromous fish floor alternatives included in the analyses.

Alternative A [1] **Tribal proposal** Gradient threshold + permanent natural barrier	Alternative C [1] Gradient threshold + Potential Habitat Breaks	Alternative D [5] **Landowner proposal** SWIFD + Potential Habitat Breaks	Alternative E [6] Gradient threshold without barrier
Waters within the anadromous fish floor. These are waters connected to saltwater and extending upstream to a *sustained* [2] *10% gradient* or a permanent natural barrier[3], whichever comes first. These waters contain main stem stream segments and associated tributaries.	Waters within the anadromous fish floor. These are waters connected to saltwater that have a *sustained gradient of 5% [or 7% or 10%]* or less, and include associated *tributaries lacking a 5% gradient increase* or permanent natural obstacle[4] at the junction with the main stem.	Waters within the anadromous fish floor. These are waters connected to saltwater that are included in widely available GIS datasets of known and presumed anadromous use (such as SWIFD or StreamNet), and include associated *tributaries lacking a 5% gradient increase* or permanent natural obstacle[4] at the junction with the main stem.	Waters within the anadromous fish floor. These are waters connected to saltwater and extending to a *sustained 5% or [7% or 10%] gradient*. These waters contain main stem stream segments and associated tributaries.

Table taken from an April 14, 2021 memo from the Anadromous Fish Floor Project Team to the Forest Practices Board's Water Typing Rule Committee.

[1] Language accepted by the FP Board at the May 2019 Board meeting.

[2] Sustained in this definition means a minimum gradient that is maintained over the full length of the reach, and doesn't at any point fall below that gradient.

[3] For the purposes of Alternative A in this analysis, permanent natural barrier follows the WDFW definition of a vertical waterfall >3.7m (~12.1 ft) in height.

[4] Natural obstacles for Alternatives C and D: Vertical step >= 3 ft, a sustained gradient >=20% that persists for a sufficient length so that the elevation increase along the segment is >= one channel width equivalent, change in gradient (identified as a point along the channel profile where the upstream looking gradient exceeds the downstream-looking gradient by 5% or more for at least 20 channel widths), and a decrease in channel size at tributary junctions of 20% or more. At the junctions of lateral tributaries with the anadromous core, the channel width criteria is ignored and only the gradient and obstacle criteria are applied.

[5] Language crafted by AFF Project Team to reflect the AFF proposal as explained by the large landowner caucus in April 2021. 'Associated tributaries' refers to tributaries laterally connected to the anadromous core. The AFF does not extend upstream beyond the upper extent of the anadromous core except on the laterally-connected tributaries.

[6] Language crafted by the project team. This alternative includes the 5%, 7%, or 10% component of Alternative C, but does not include the natural barrier component of Alternative A or the 5% gradient increase component of Alternative D.

Additional Alternatives A3 and A4:

In addition to the AFF alternatives approved by the water typing subcommittee (Table 1), the AFF Project Team analyzed two alternatives that combine aspects of Alternatives A and D. Specifically, the new alternatives incorporated the 10% gradient threshold from Alternative A and used the concept of an ‘anadromous core’, defined using established data on known and presumed anadromous distribution, from Alternative D as a starting point to define anadromous waters. Alternative ‘A3’ is defined as all waters included in the SWIFD GIS database of documented (observed) and presumed anadromy, plus upstream associated waters occurring below a sustained gradient of 10% or a permanent natural barrier, whichever comes first. For the purposes of Alternative A3, permanent natural barrier is defined using the WDFW definition (see Table 1). Alternative A4 is identical to A3, except it uses a channel-width-based natural barrier definition based on professional judgement and experience, described below (refer to the Appendix A for a diagram illustrating the differences between Alternatives D, A3 and A4).

Non-vertical obstacle:

- Channels < 5 feet in width: sustained gradient ≥ 20% for ≥ 100 feet (30 meters) without resting areas.
- Channels 5 – 10 feet in width: sustained gradient ≥ 20% for ≥ 250 feet (76 meters) without resting areas.
- Channels > 10 feet in width: sustained gradient ≥ 20% for ≥ 515 feet (160 meters) without resting areas.

Vertical obstacle (permanent natural features):

- Channels < 5 feet in width: near vertical drop ≥ 5 feet in height (1.5 meters)
- Channels 5 – 10 feet in width: near vertical drop ≥ 8 feet in height (2.5 meters)
- Channels > 10 feet in width: near vertical drop ≥ 12 feet in height (3.7 meters)

Questions addressed in this report

The Anadromous Fish Floor workgroup collaboratively developed questions of interest to guide the spatial analysis:

a. What is the distribution of stream lengths (both positive and negative) between anadromous fish presence points, concurred F/N breaks [1] and the proposed tribal and landowner proposals (including 5%, 7% and 10% AFF gradient thresholds)?

b. What proportion of anadromous fish distribution points and concurred F/N breaks points are observed above and below the proposed AFF overlays?

c. What is the distribution of maximum sustained channel gradient downstream from known and presumed anadromous fish points and concurred F/N breaks?

Methods

Approach

The general approach used was to assemble a database of existing known and presumed fish occurrence data to serve as reference points for comparing our AFF alternatives. This method of model comparison against independent field data is a standard approach used in the physical and biological sciences. It allows for evaluation of model ‘success’ as judged in comparison with the data. Relative performance may be judged by the distances between the model prediction and the fish data. Specific to the AFF analysis, this means model ‘error’ may be evaluated by tallying the length of stream where modeled AFF

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[1] F/N break is the current regulatory point that divides fish habitat from non-fish habitat.

alternatives fall short of or extend beyond the various types of fish distribution data. How the fish reference data were generated and what species they represent all influence the interpretation of the model performance.

Below, we describe the methods used to collect the fish reference data and provide information necessary to aid in the interpretation of the AFF model results. Multiple watersheds and basins in western Washington are represented by the fish reference data, including Skagit/Sauk Rivers, Sol Duc/Calawah/Bogachiel Rivers, Wynoochee/Humptulips Rivers, North Fork Skokomish, Mill Creek/Skookum Creeks, Kalama River, and Stillman Creek (Error! Reference source not found.).

Figure 1. Fish reference data were compiled from shaded areas of the map and used in the spatial analysis.

Fish reference data

The fish reference data used in the AFF analysis came from a variety of sources, some of which incorporate both observed and 'presumed' fish occurrence data. Field data identifying the extent of fish use are typically developed using a combination of observed fish occurrences and/or best professional judgement extending a presumption of fish use beyond observed fish use where fish use at some other time can reasonably be presumed. Within field surveys, presumption of fish occurrence is commonly based on considerations of channel size, gradient, species present in similar or nearby streams, habitat requirements of the different life history phases of individual species, presence of upstream or downstream barriers to fish passage, and other factors. Therefore, it is reasonable to assume that presumed occurrence may include some degree of uncertainty in both the upstream and downstream directions, whereas observed occurrence should have uncertainty only in the upstream direction.

Given the temporal variability in fish use of streams often observed near the upper extent of their habitats, the distribution of fish may change over time. Variability in population abundance, streamflow, habitat quality, etc. may temporarily displace fish from habitats occupied at other times. Seasonal use of habitats by fish may lead to errors in the interpretation of single visit fish survey results intended to determine the upper extent of fish habitat. Conversely, presumption of fish habitat may lead to assumed fish waters upstream of habitat used by fish. Each source of fish data used in the spatial analysis is described below.

1. Statewide Integrated Fish Distribution (SWIFD). These data are jointly managed by the western Washington treaty tribes and WDFW. They were originally developed as part a 'limiting factors analysis' (LFA) project which brought together knowledgeable fish biologists from tribes, state agencies and other interested parties to map known and presumed fish distribution based on observations of fish presence and assumptions of habitat suitability (explained above). As such, these data represent known and presumed[2] anadromous presence, not necessarily the delineation between downstream anadromous presence and upstream anadromous absence. Importantly, we removed 'modeled' anadromous distribution points (termed 'gradient-accessible' in the SWIFD database) because we found these points to be unreliable in early review. There are known spatial inaccuracies in the SWIFD dataset (including the documented and presumed points) resulting from the creation of the data on coarse resolution maps and the subsequent transfer to digital format. There are 623 points in this dataset, of which 498 are documented (observed) and 125 are presumed.
2. Skagit-LFA. These data came from a similar source as the original SWIFD dataset, but have received several rounds of quality control and interpretation since the original LFA effort. First, Marks et al. (2004) field verified 10% of the Skagit LFA Coho points for Coho presence and

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[2] From the SWIFD documentation (O'Connor, 2002): 'Presumed: Aquatic habitat lacking reliable documentation of fish use where, based on the available data and best biological opinion/consensus, fish are presumed to occur. For migratory fish, such habitat will extend upstream to the end of the stream OR to the first known natural barrier (including sustained 12% stream gradient or small stream size). Best biological judgment includes consideration of suitable (species-specific) habitat availability, life history strategies, proximity and connectivity to adjacent "Documented" habitat sections or logical extrapolation of range from similar systems.'

association with natural barriers. They found that 97.5% of the evaluated points accurately identified Coho habitat, but only 65% were determined to represent the end of Coho habitat. Later, Skagit River System Cooperative staff classified each of the Skagit LFA points as being associated with known permanent natural barriers, human-made barriers, the end of a channel (i.e. the upstream extent of wetted habitat in low gradient channels), or no association with a habitat termination feature. For this report, we only included Skagit LFA points associated with permanent natural barriers and the end of wetted habitat. Therefore, these data may be regarded as observed fish presence. There are 49 points in this dataset.

3. U.S. Forest Service. These data came from a study conducted by the U.S. Forest Service in the Olympic Peninsula region. The data contain information on fish species collected at geolocated positions on the stream network; using the species information, we were able to separate locations of anadromous fish use from locations of resident fish use. Therefore, these points may be interpreted as representing observed anadromous and resident fish presence. This dataset contains 17 anadromous points and 42 resident fish points.
4. Squaxin Island Tribe. These data were collected as part of an effort to understand juvenile salmon use in the usual and accustomed territory of the Squaxin Island Tribe. Field biologists collected geolocated positions of Coho observations. Therefore, this dataset represents observed juvenile Coho presence data in the Skookum Creek and Mill Creek watersheds. There are 35 points in this dataset.
5. Water Type Modification Forms. These data represent regulatory water type breaks between water types (fish/non- fish habitat) in our analyzed watersheds. The concurred breaks incorporate the upper extent of fish occurrence as determined in a protocol survey, and in many cases also include presumed habitat extensions upstream based on best professional judgement and variable requirements for regulatory acceptance. In some watersheds, there were unresolved spatial errors introduced into the locations of these data during the transfer of points onto the synthetic stream network. Therefore, we vetted a random selection of these points and retained 94 points out of 150 points reviewed that were assessed to be verified field-based concurred fish habitat type breaks, and that were correctly located spatially in the synthetic stream network. Additionally, we added 390 F/N break points that had been similarly vetted during a previous analysis completed for the Stillman Creek and Kalama River basins. We found that 35 of the 94 F/N points randomly sampled and vetted also existed in the vetted Stillman / Kalama dataset. While these vetted F/N data are located throughout our study watersheds, they more heavily represent the southwest Washington region; the vast majority, but not all, of these points were concurred. These data represent our best approximation of the end of fish habitat used by any species of fish. There are 2 anadromous and 447 resident fish reference points in this dataset.

Given the preceding discussion and descriptions, we assume observed anadromous occurrence data represent anadromous presence but not necessarily absence of anadromous use farther upstream. Presumed anadromous occurrence data incorporate stream reaches beyond observed anadromous fish occurrence with the potential for spatial errors in the upstream or downstream direction (we assume these points do not necessarily represent the upper extent of anadromy, but their locations may include some unknown spatial error in the upstream or downstream direction). The F/N break data represent the end of fish habitat, while recognizing there may be spatial errors in these points in both upstream and downstream directions due to the presumption of habitat during the protocol survey and review process.

Integrating the fish data from these diverse datasets included categorizing each fish reference point into one of four types:

1. SWIFD_Anadromy: Point data from the Statewide Integrated Fish Distribution (SWIFD) database indicating observed or presumed presence of anadromous fish. As discussed above, these fish points do not necessarily represent the upstream extent of anadromous fish use, and are subject to some unknown level of spatial error, especially in the 'presumed' category.
2. Other_Anadromy: Point data other than SWIFD indicating presence of anadromous fish. Most of these points were observed occurrence (see descriptions above). These fish points are treated as presence only, not necessarily the upstream extent of anadromous fish use. Composed of data from the US Forest Service, Squaxin Island Tribe, and Skagit-LFA datasets.
3. 'Other fish': Point data indicating locations of fish of resident or unknown life history type. These fish points represent known occurrence only, not the upstream extent of fish occurrence. Composed of data from the US Forest Service dataset. These points are all observed fish occurrences. N = 106.
4. Concurred_FN: Concurred F (fish bearing) to N (non-fish-bearing) water type break locations as identified and documented through water type modification forms. At a minimum, these data incorporate the surveyed upper extent of fish use; in many cases, they incorporate presumed habitat upstream of observed occurrence.

Synthetic Stream Layer

TerrainWorks used high resolution lidar to develop digital elevation models and delineate synthetic stream layers for each selected watershed (see Appendix B for detailed descriptions of the methods used to create the synthetic stream network). The synthetic stream network used elevation data from lidar along each stream to map channel gradient, modeled channel width, barriers, and obstacle features at a resolution of approximately 1-2m. These channel features formed the basis for modeling the proposed AFF alternatives and the channel length measurements used to evaluate the AFF alternatives. Importantly, 'sustained gradient' was calculated using an approach that mimicked how it might be found in a channel unit survey in the field, in which pools (relatively flat areas), riffles, glides and cascades are delineated based on changes in gradient. For the purposes of identifying the termination point of AFF alternatives that used thresholds in sustained gradient, sustained gradient was defined as a reach length equivalent to at least 20 channel widths within which no 'sub reach', or individual channel unit (pool, riffle, etc.) fell below the threshold gradient. For example, where a 10% gradient threshold was identified as the endpoint of Alternative A, no low gradient features which may function as resting areas, such as pools or low gradient riffles, should be identified within 20 channel widths of the first (lowest) section of channel that exceeds 10% gradient.

Strategies to address uncertainty

We employed several strategies to reduce uncertainty in the results. First, the project team conducted extensive review of the synthetic stream network, visually checking for errors in stream location and errors in the placement of fish data points. We culled the SWIFD dataset to remove modeled (‘gradient accessible’) fish distribution points and retain only documented or presumed points. We selected a random sample of the F/N break point data and manually checked each one against the public water type modification form for spatial accuracy and for concurrence, keeping only those points that were correctly located in the synthetic stream network and that represented a surveyed end of fish habitat. We took a conservative approach to life history labels based on fish species, for example using the tag ‘life history unknown’ rather than ‘anadromous’ for occurrence data for *Oncorhynchus mykiss* or *O. clarkii* (which have anadromous and resident expressions).

Similarly, we removed ‘outliers’ from the steepest downstream gradient results using an objective ‘Tukey’s Fences’ approach recommended by TerrainWorks. During data analysis, we observed that some data points on channels near the edge of a flood plain were digitized such that they fell on the valley slope rather than within the floodplain and were then incorrectly snapped to steep channels above the floodplain. Other points were placed on road prisms when they should have been placed in the channel below. These spatial placement errors may have affected the maximum downstream gradient results but did not greatly affect the channel distance results because the ‘snapped’ points fell close to their original locations; therefore, they were removed from the steepest downstream gradient results only.

Web-Based Map

To aid with ongoing project-team review of the data products and analyses, TerrainWorks uploaded the synthetic channel networks and AFF fish distribution database points to a web-based map. With this map, AFF-project-team members reviewed data products and identified errors in the database and synthetic networks, reviewing nearly 12,000 data points.

Spatial Analyses

The sums of all distances between modeled AFF alternative end point location and each fish reference point were calculated. Stream lengths where AFF alternatives extended upstream of reference points were assigned a positive distance. Stream lengths where AFF alternatives ended downstream of a fish reference data point were assigned a negative distance. Distances for modeled AFF points occurring above fish reference data points and within streams with unknown fish use (no reference data classification) were also summarized. These data can provide the basis for evaluating the performance of AFF alternatives.

Each alternative was compared by binning stream reaches into categories defined by the spatial relationships between the most upstream occurrence of each fish point type and the modeled AFF locations and tallying the lengths within each of these overlapping reach categories. For the spatial analysis, there were four primary categories of interest the AFF Workgroup identified as useful to addressing the spatial analysis questions. These categories describe whether each AFF alternative terminates upstream or downstream of the anadromous or F/N water type break reference point and therefore represent the ‘error’ or ‘misfit’ in the modeled extent of each AFF alternative (Figure *2*).

Standard statistical approaches employed to characterize performance of spatially explicit GIS stream network models rely on measurement of stream length distances between the predicted points and locations of independent validation points. Calculations are then conducted using those data that describe the accuracy and precision of the modeled points. Common examples of performance metrics include calculations of the mean error distance (average of upstream and downstream distances) and total error distance (sum of the absolute value of upstream and downstream error distances). These measures of performance are typically used to identify best performing alternatives that meet the intended performance objectives for the model.

We have elected not to provide those statistical metrics in this report and instead present the information graphically to allow for a visual comparison of the performance of the AFF alternatives we analyzed. This decision was based on several factors:

- The reference data employed in this analysis are “found” data, employed variable sampling protocols, and were not collected in an optimal manner for the purpose of this analysis.
- We have no ability to reliably characterize the frequency or magnitude of reference data errors.
- The locations of channel features derived from the LiDAR stream network employed in this analysis have not been field validated, and it is unknown how well they represent features found in actual stream channels.

Additionally, the AFF workgroup has not received clear guidance from the Forest Practices Board describing the specific performance expectations they have for the AFF alternatives, leading to a lack of context with which to interpret the traditional statistical results.

Graphical representations of total distance above and below each reference data category and in streams with no associated reference data (unknown streams) are provided in the results section. Relative performance of AFF alternatives may be evaluated by visual comparison of the magnitude and balance of errors for each alternative.

Given the interpretation of the anadromous data as being presence and presumed-presence only (not absence), we also chose to emphasize the undershoots of the anadromous data and the overshoots of the F/N data as the important metrics for alternative comparison (Figure 2). Reaches within the AFF that are upstream of known or presumed anadromous fish location points are categorized as ‘uncertain anadromous’ to reflect the interpretation of the anadromous data as ‘presence-only’ data, not ‘presence-absence’ (see discussion section). Additionally, the workgroup identified the length of stream within the AFF for each alternative on streams with no fish data as potentially important information relevant to policy decision making.

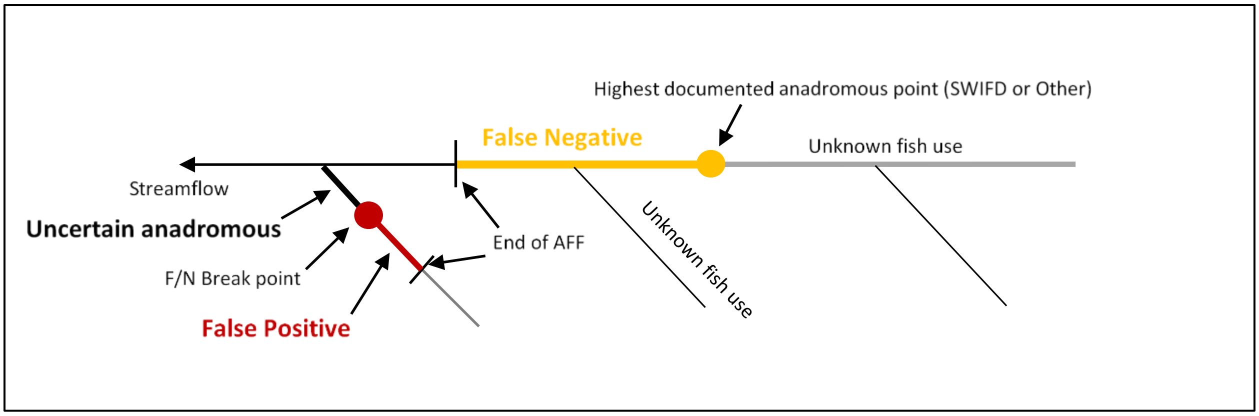


Figure 2. Stream reach schematic illustrating the stream categories used to evaluate the AFF alternatives.

Once the streams were assigned to categories, the cumulative lengths were calculated for each stream category and compared across the different AFF alternatives (**Figure 3**).

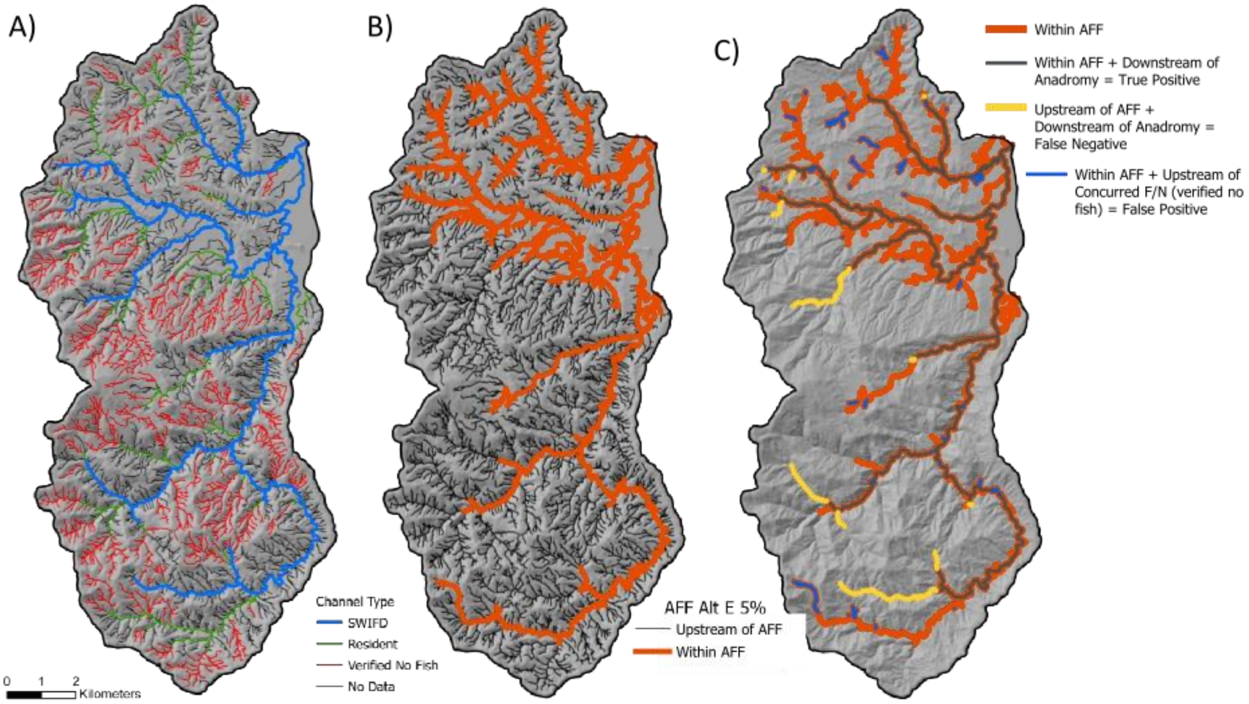


Figure 3. Maps illustrating the analysis process for the Stillman Creek basin in southwest Washington. The colored lines represent the different channel classifications used in the spatial analysis. A) channel classes based on fish presence. This basin lacks data for 'other anadromy' and 'unknown life history', so there are fewer total channel classes. B) Modeled AFF for Alternative E5% (as an example). C) Overlay of the modeled AFF on the channel classes based on the available fish data. These maps are presented at the scale of an entire drainage basin to illustrate the analysis process, not to portray results. See figure 4 for maps shown at a scale that is useful for interpretation of the results.

Additional analyses

Data were also analyzed to address questions about (1) the proportion of fish reference points (anadromous and F/N break) upstream and downstream of the different AFF alternatives, and (2) patterns in the steepest sustained channel gradients observed downstream from the highest anadromous and F/N break points in the dataset.

Results of the Spatial Analysis

Figure 4 shows the modeled AFF results for Alternative A (top panel), Alternative D (middle panel), and the maximum downstream sustained gradients in a portion of the Stillman Creek watershed (Lost Creek headwaters).

Similarly, Figure 5 shows the modeled AFF results for Alternative A (top panel), Alternative D (middle panel), and the maximum downstream sustained gradients in a portion of the Kalama watershed.

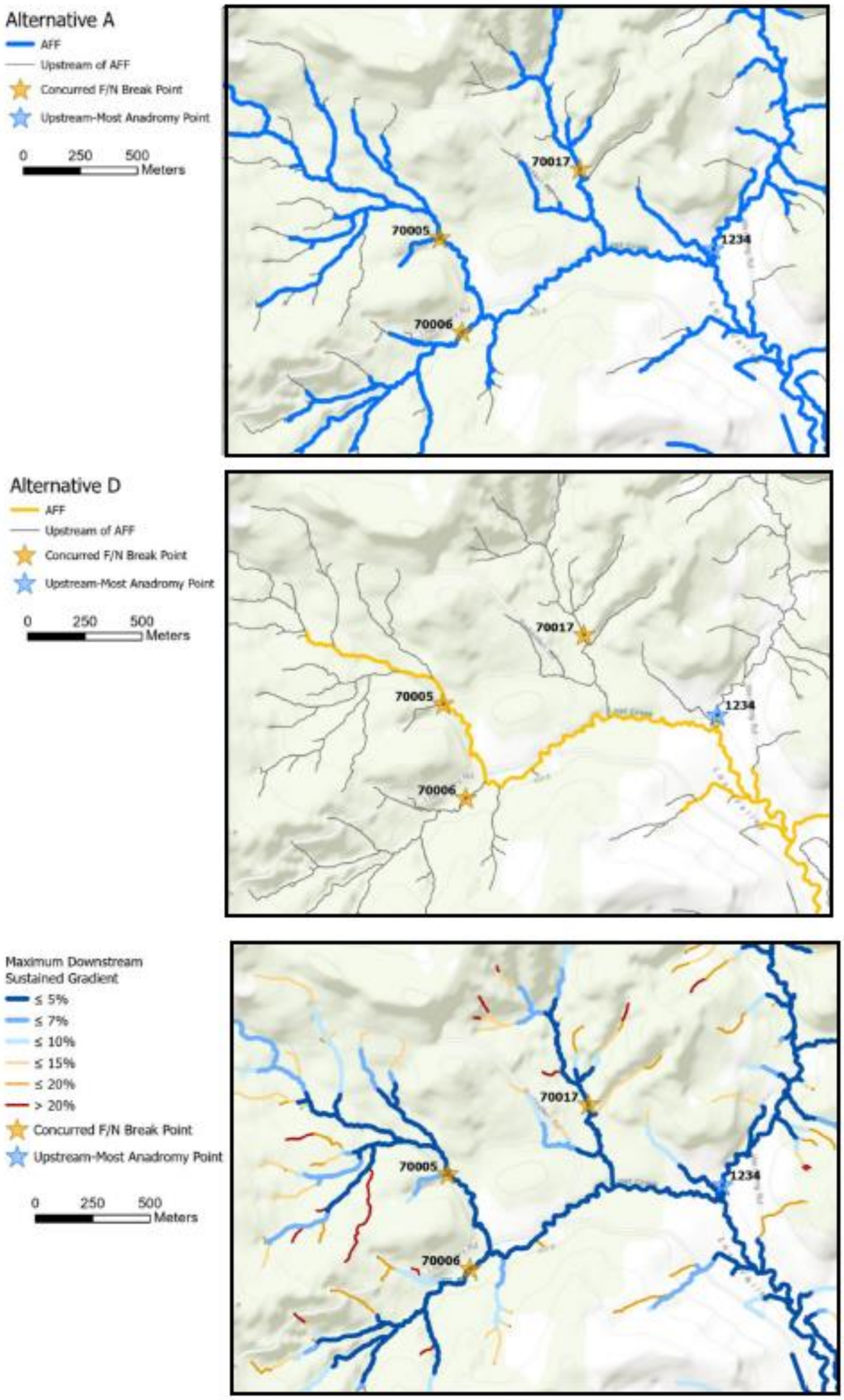


Figure 4. Example maps from a portion of the Stillman Creek basin in southwestern Washington. The top panel shows modeled Alternative A; the middle panel shows modeled Alternative D; the bottom panel shows the maximum downstream sustained gradients.

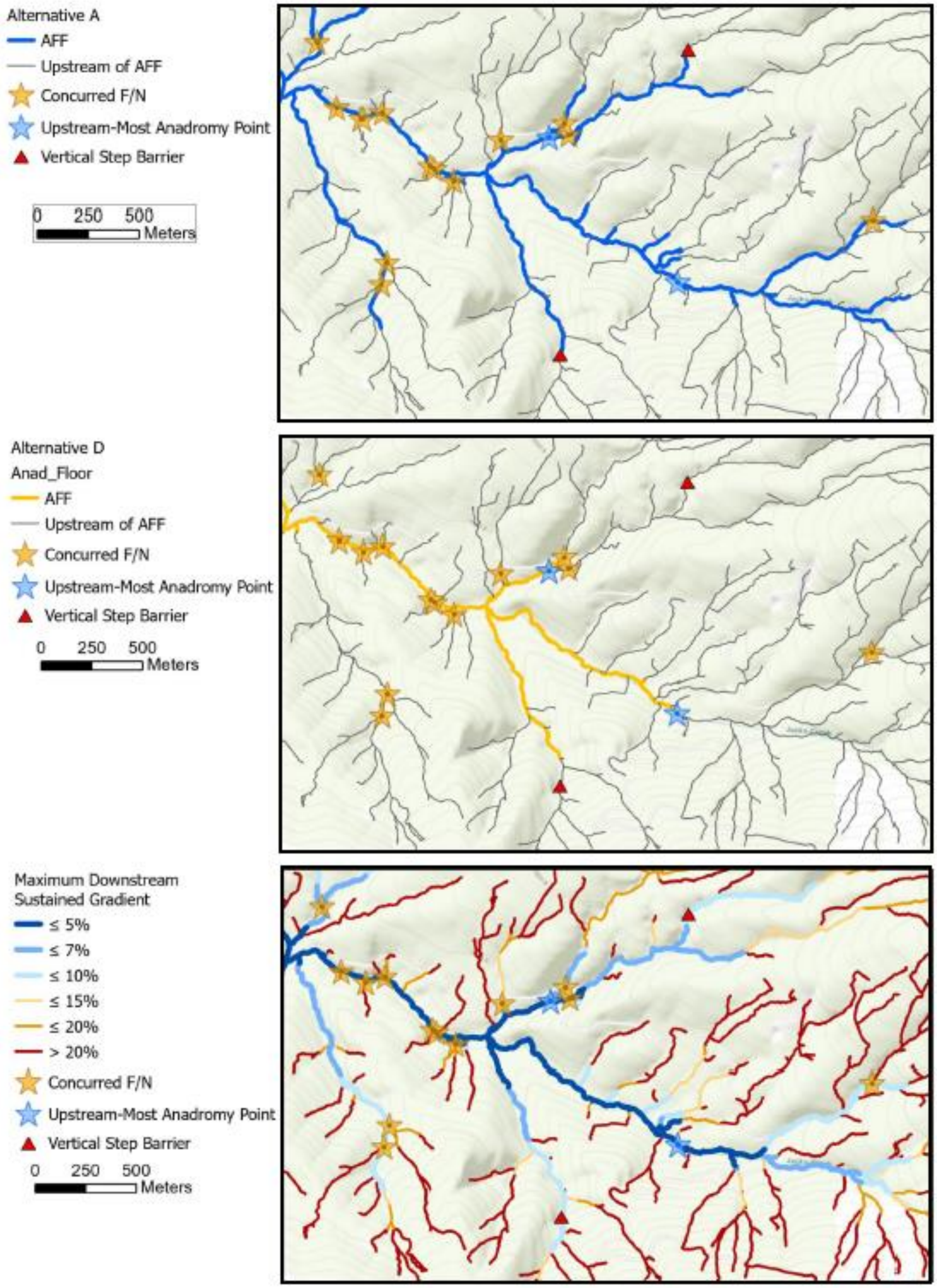


Figure 5. Example maps from a portion of the Kalama watershed in southwestern Washington. The top panel shows modeled Alternative A; the middle panel shows modeled Alternative D; the bottom panel shows the maximum downstream sustained gradients.

The modeled alternatives varied in their total length, as shown in Figure 6. Alternative C10% and Alternative E10% had the greatest overall length, and Alternative D had the shortest length (**Figure 6**). As expected, the total length of the AFF shortened as the gradient threshold values decreased. Alternative A had a similar total length to C7% and E7%, due to the addition of natural barriers in the definition of Alternative A.

The vast majority (97.6%-98.7%, depending on alternative) of the modeled AFF length in the watersheds we analyzed was covered by high-resolution lidar data (**Figure 6**). Because the channel attributes used to form the end of the modeled AFF alternatives were best measured using lidar data, we report results using only the portions of the total stream systems that had lidar coverage. In the following paragraphs, we address the questions of interest formulated in the workplan and stated earlier in this report.

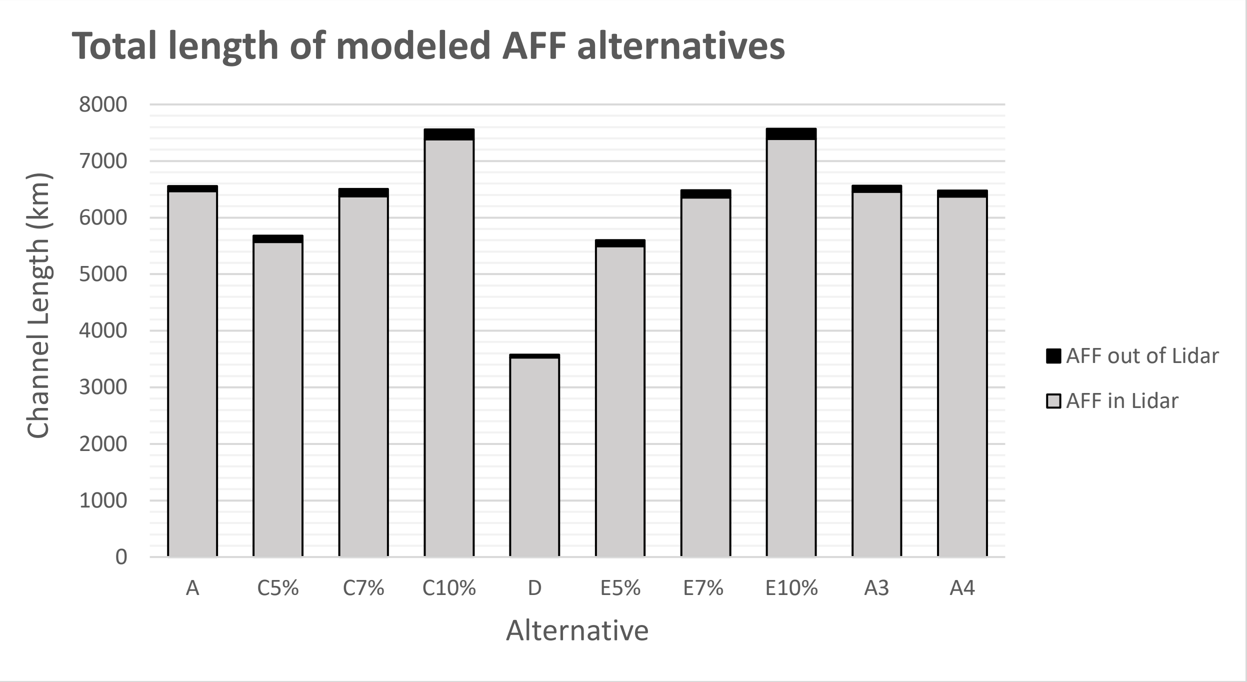


Figure 6**.** Modeled AFF length within and without portions of the analyzed watersheds covered by lidar topographic data.

Addressing the questions of interest

a. *What is the distribution of stream lengths (both positive and negative) between anadromous fish distribution points, concurred F/N breaks and the proposed tribal and landowner proposals, including 5%, 7% and 10% AFF gradient thresholds?*

Channel length above and below the fish reference data for each alternative are presented in figures 6 through 12 and in table 2. These results include the additional alternatives A3 and A4.

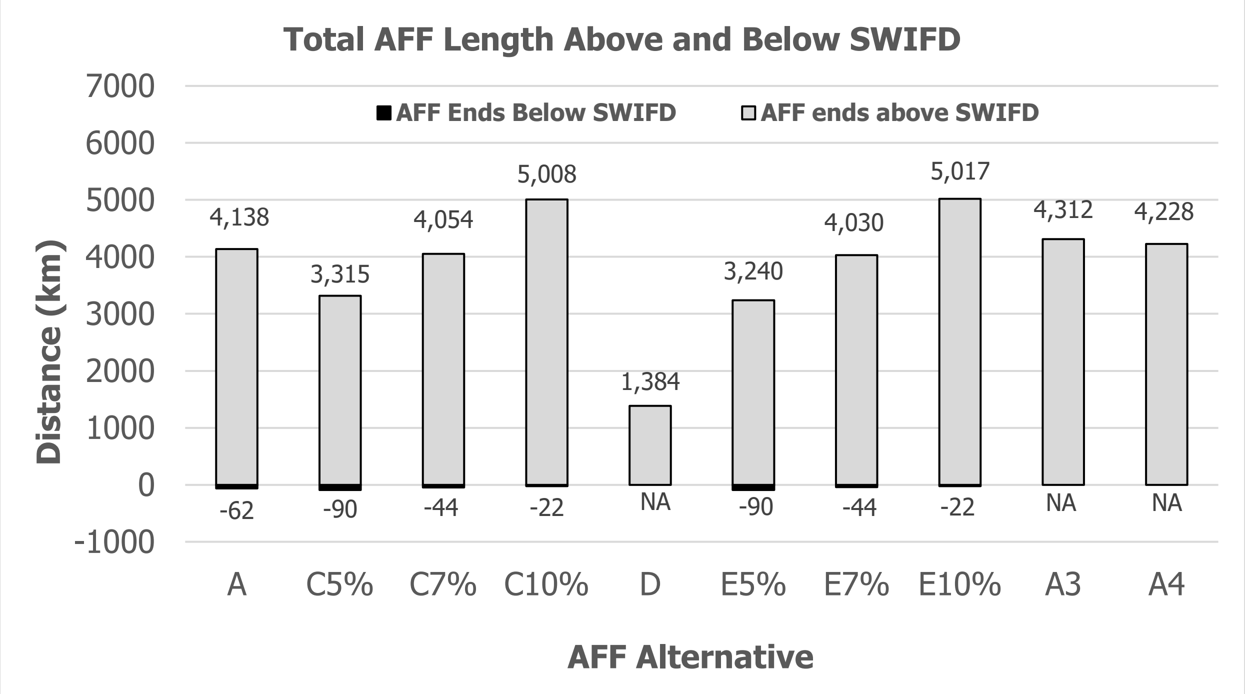


Figure 7. Distances of the modeled AFF alternatives above and below the SWIFD anadromous data. Alternatives D, A3 and A4 are defined using SWIFD, and so downstream distances are not included. The upstream distances represent the length of those alternatives beyond SWIFD.

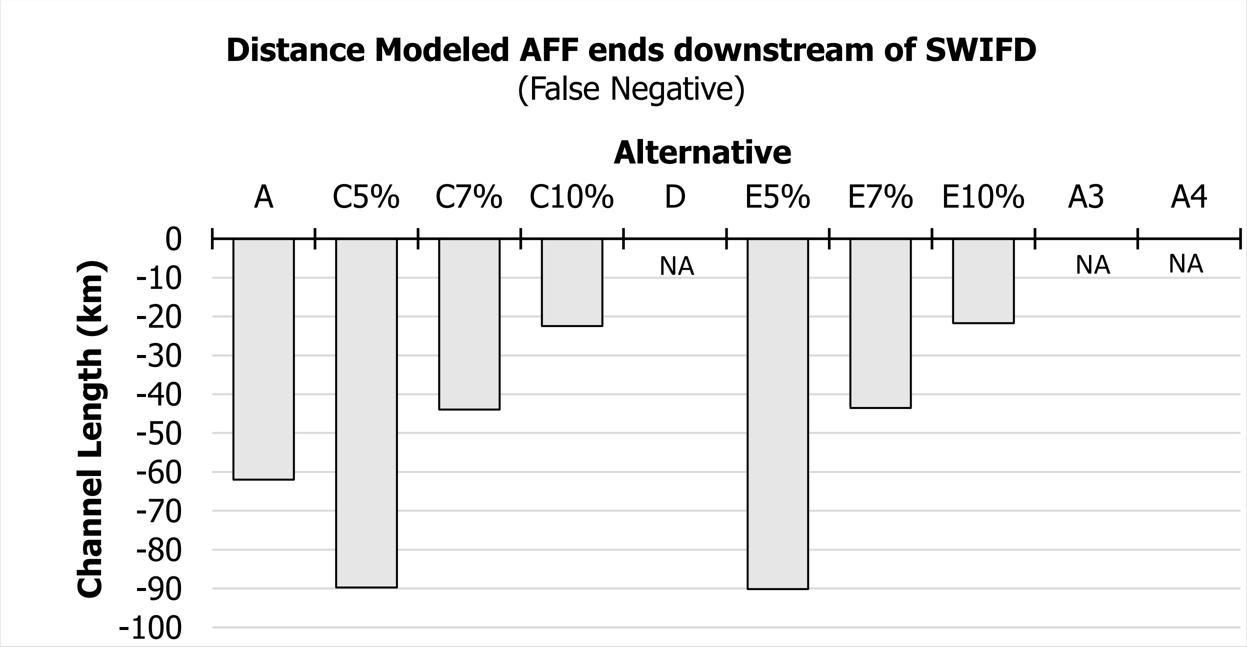


Figure 8. Bar chart showing the distance the modeled AFF alternatives end downstream from SWIFD. Alternatives D, A3 and A4 are excluded from this plot because they are defined by the SWIFD stream extent.

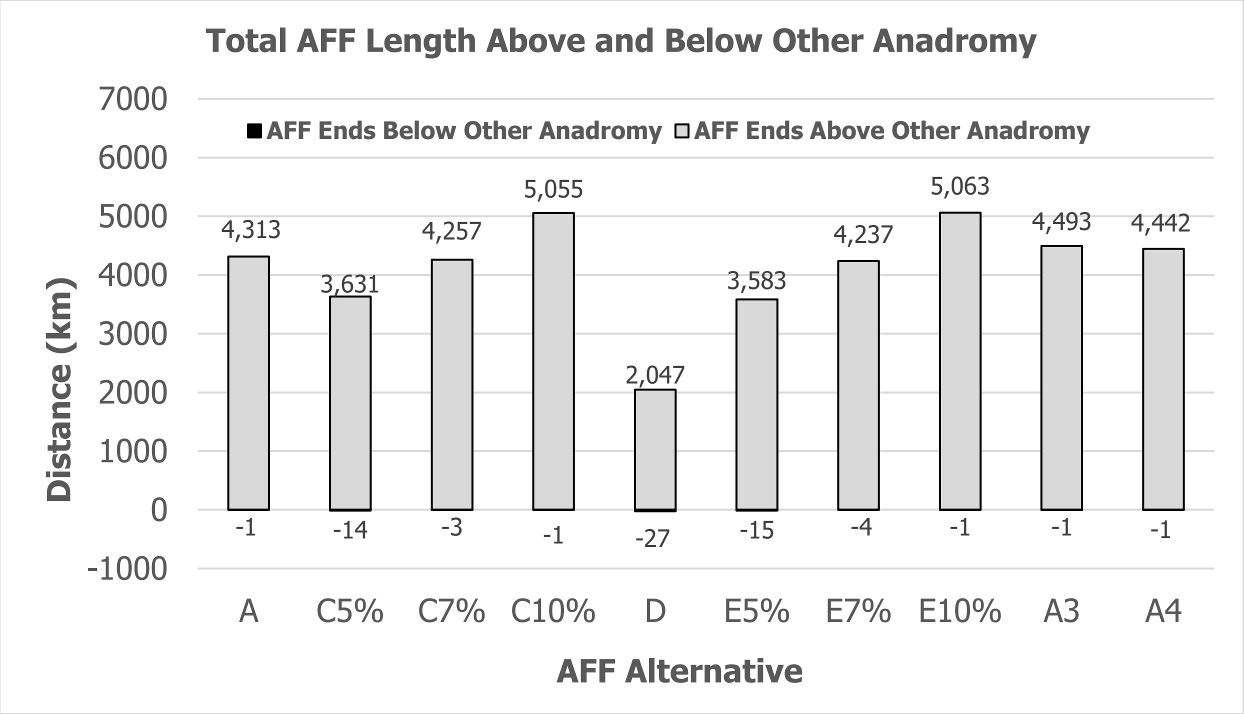


Figure 9. Distance the modeled AFF alternatives terminate above and below the ‘other anadromy’ data points.

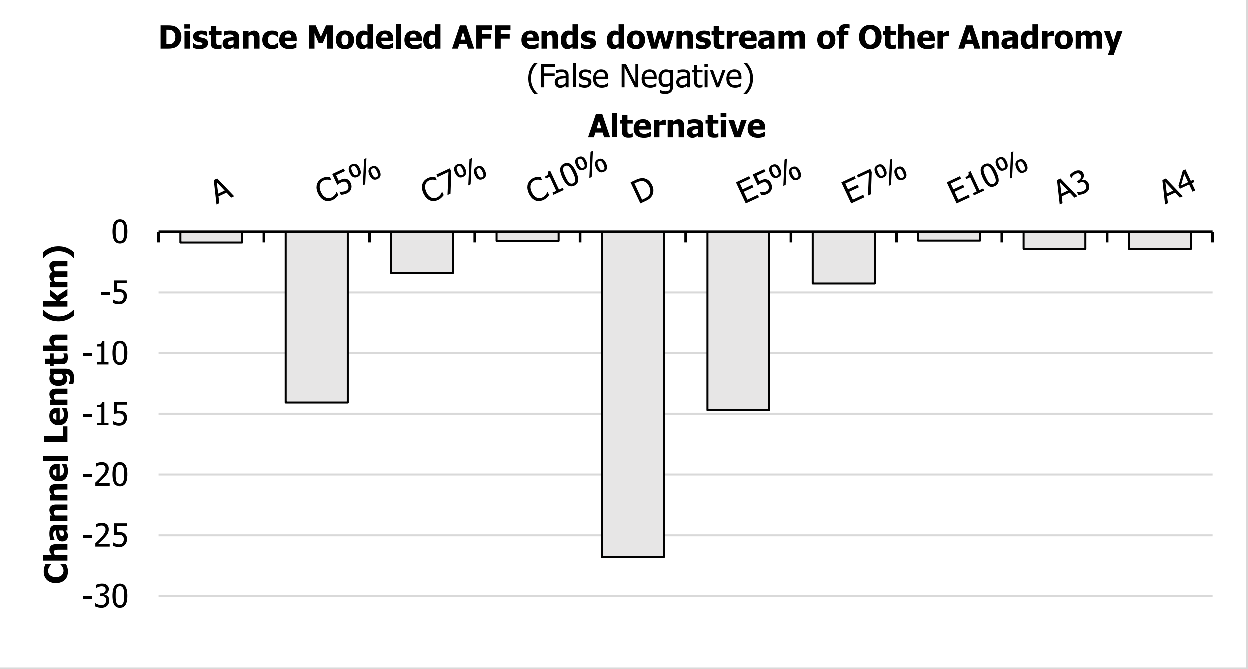


Figure 10. Bar chart showing the length of stream in which the modeled AFF ends downstream of the ‘other anadromy’ data (False Negatives).

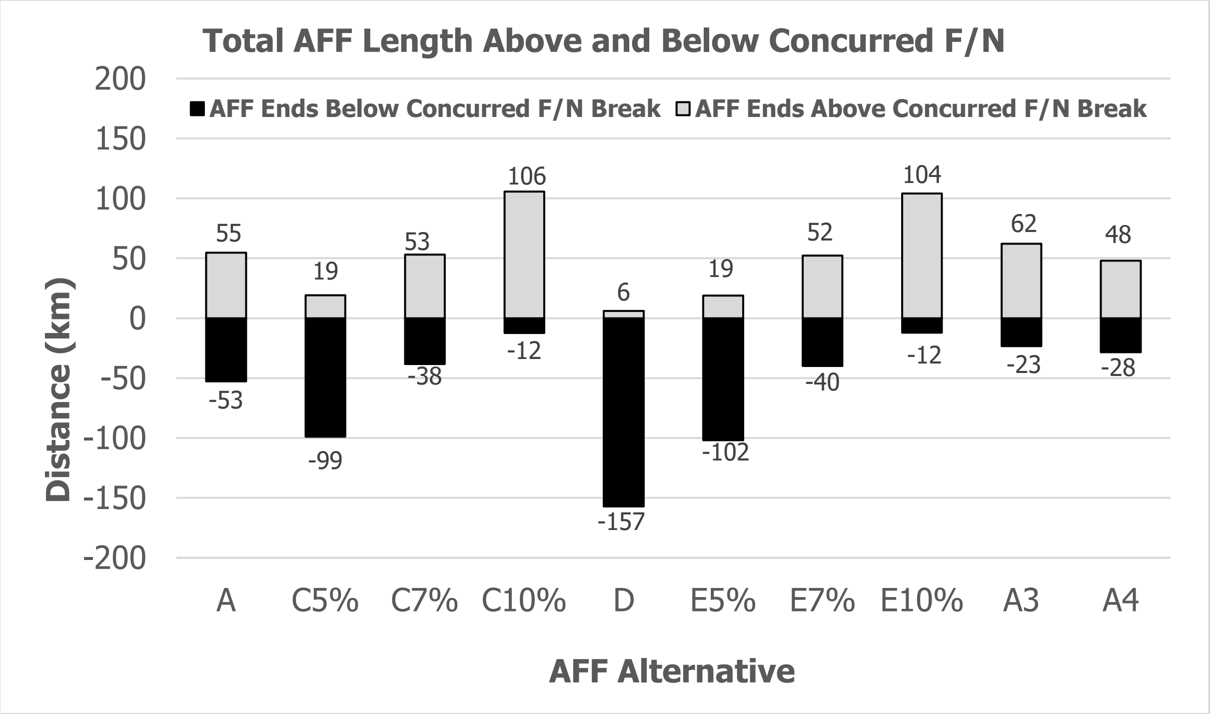


Figure 11. Distances that the modeled AFF alternatives terminate upstream and downstream of the F/N break point data. The positive bars (grey) are referred to as 'false positives' in the framework of Figure 2.

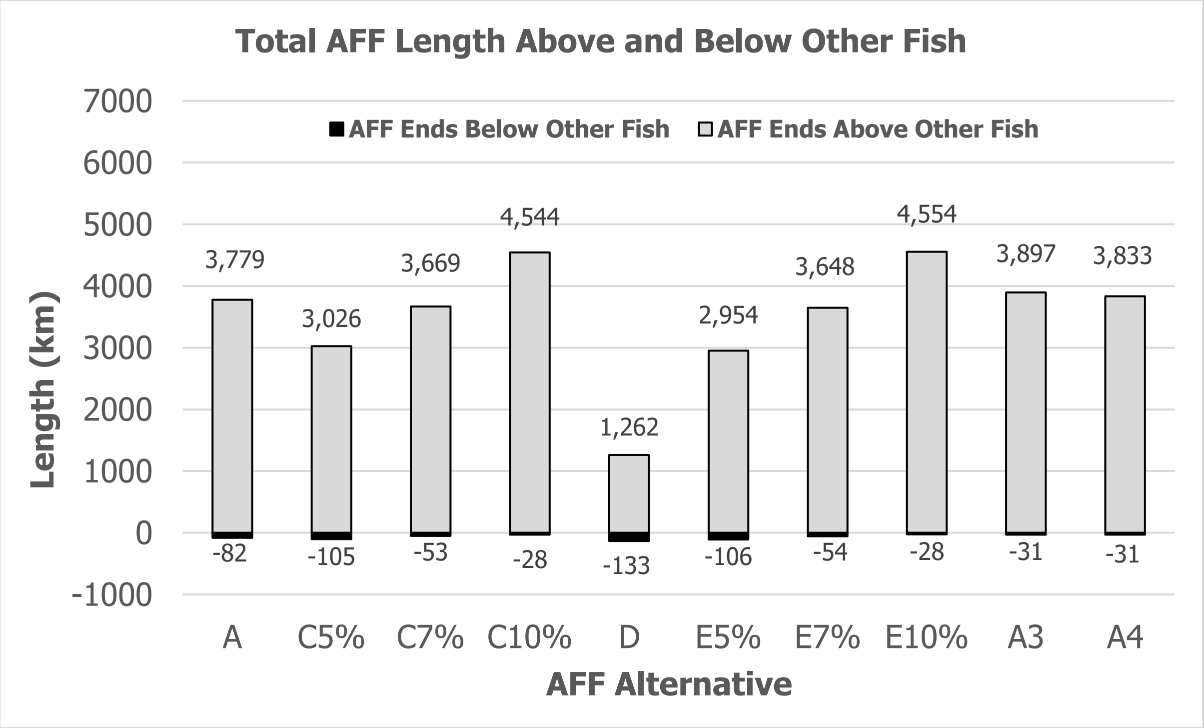


Figure 12. Channel distances of the modeled AFF alternatives above and below ‘other fish’.

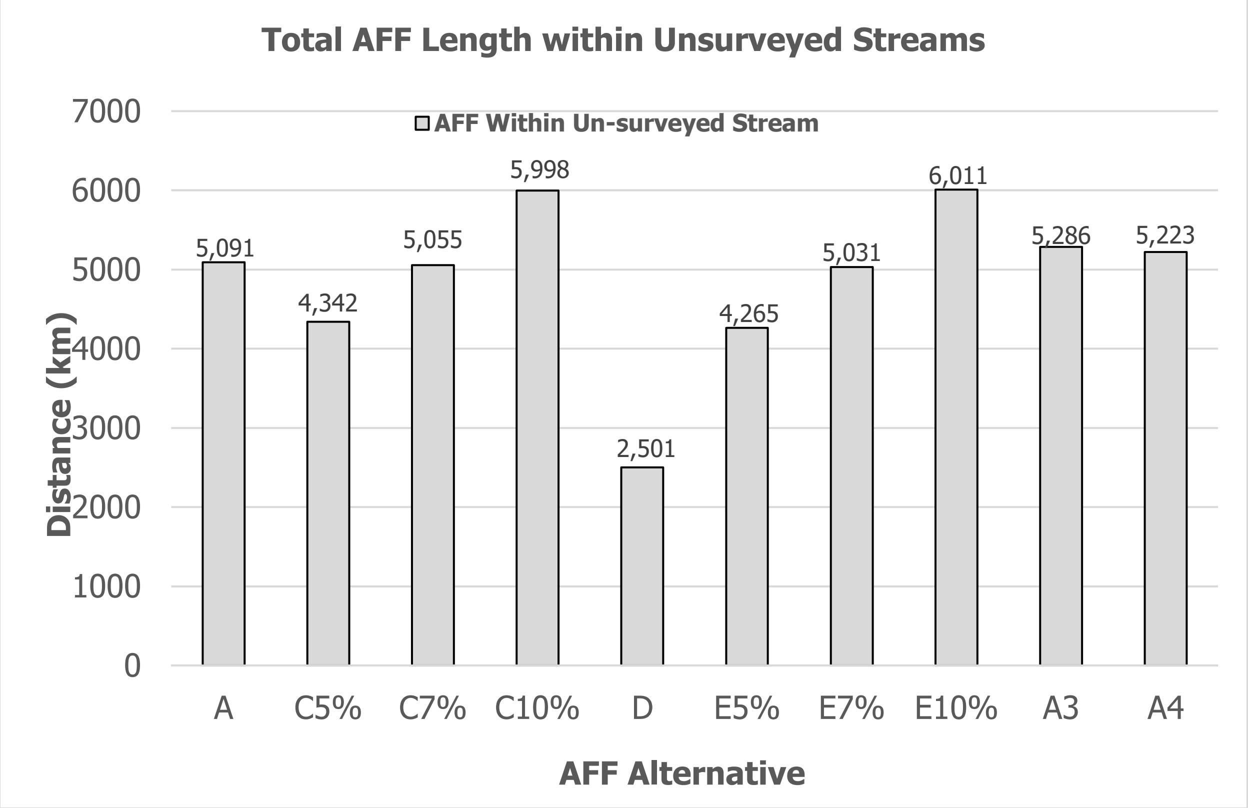


Figure 13. Channel distance where the modeled AFF alternatives extend into streams with no fish data (anadromous or F/N break).

Table 2. Cumulative channel lengths (kilometers) for each AFF alternative and stream categories.[1]

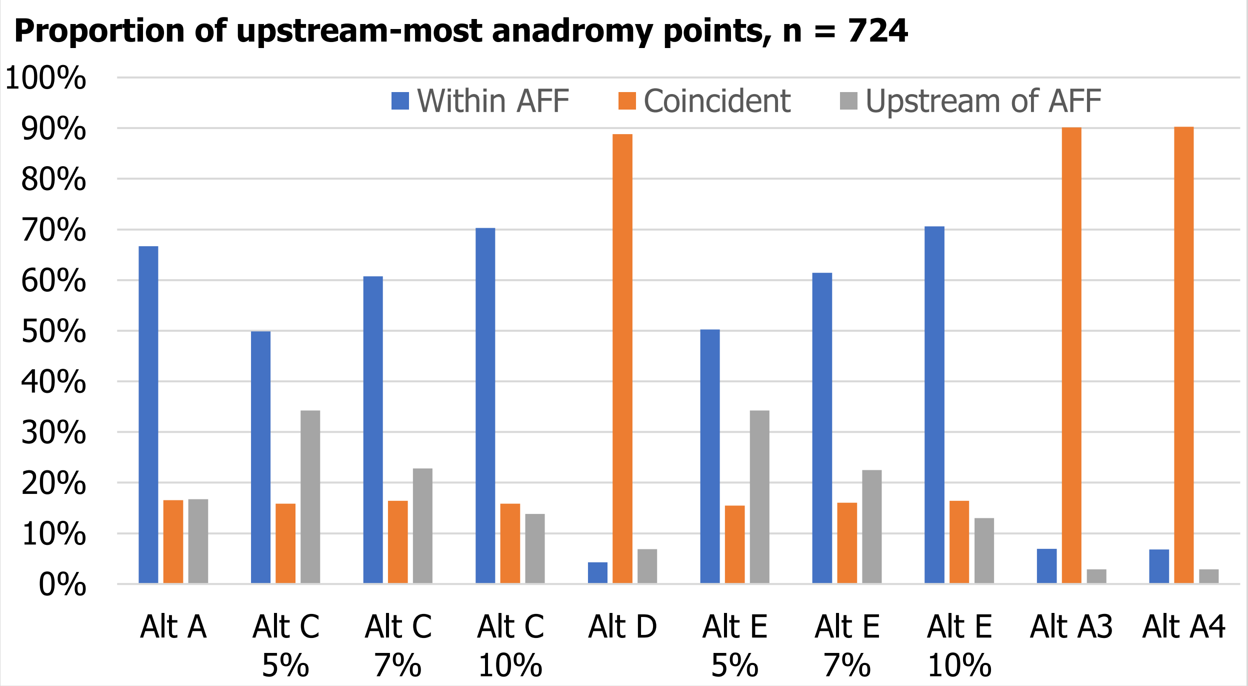
	AFF Alternative									
Stream category	**A**	**C5%**	**C7%**	**C10%**	**D**	**E5%**	**E7%**	**E10%**	**A3**	**A4**
Total AFF length	6468	5568	6378	7381	3527	5495	6356	7391	6455	6371
AFF in streams with no fish data	5014	4241	4935	5831	2451	4169	4913	5842	5189	5125
AFF overlap with fish data										
Overlap of AFF and all anadromy	2151	2119	2168	2191	NA	2119	2168	2191	NA	NA
Overlap of AFF and SWIFD	2081	2053	2099	2120	NA	2052	2099	2121	NA	NA
Overlap of AFF and other anadromy	1053	1040	1051	1054	1028	1040	1050	1054	1053	1053
AFF ends downstream of highest fish points										
AFF ends downstream of all anadromy	-62	-94	-45	-22	NA	-94	-45	-22	NA	NA
AFF ends downstream of SWIFD	-62	-89	-43	-22	NA	-90	-43	-21	NA	NA
AFF ends downstream of other anadromy	-0.88	-14	-3.39	-0.75	-26.79	-14.69	-4.26	-0.72	-1.41	-1.40
AFF ends downstream of other fish	-81	-104	-53	-28	-133	-105	-53	-27	-30	-30
AFF ends upstream of highest fish points										
AFF ends upstream of all anadromy	4078	3256	3993	4948	1340	3182	3970	4957	4242	4158
AFF ends upstream of SWIFD	4138	3314	4053	5008	1384	3240	4029	5017	4311	4228
AFF ends upstream of other anadromy	4312	3631	4256	5054	2047	3582	4237	5062	4492	4441
AFF ends upstream of other fish	3778	3025	3668	4543	1262	2954	3647	4553	3897	3832
Relation of AFF with F/N Break points										
AFF ends below F/N break	-52	-99	-38	-12	-157	-101	-39	-12	-23	-28
AFF ends above F/N break	55	19	53	106	6	19	52	104	62	48

[1] All lengths given in kilometers. Results should be compared between alternatives (within rows), not between stream categories (within columns) because the stream categories use reference fish occurrence data with different sample sizes.

***b**: What proportion of anadromous fish distribution points and concurred F/N break points are observed above and below the proposed AFF overlays?*

Alternatives using larger gradient thresholds had a larger proportion of anadromous and F/N break points within their modeled extent; alternatives that used smaller gradient thresholds had higher proportions of anadromous and F/N break points upstream of their modeled extent (**Figure 14**). Not surprisingly, a relatively higher proportion of F/N break points were observed upstream of the AFF proposals than the anadromous points (**Figure 14**, lower panel)). The F/N break points are typically based on resident fish observations which tend to occupy habitats higher into watersheds than most anadromous fish.

Alternatives D, A3 and A4 had a high proportion of anadromous fish points coincident with the end of the AFF due to the use of the SWIFD data in their definition. This issue of Alternatives D, A3 and A4 using SWIFD in their definition creates some ambiguity in the interpretation of **Figure 14** (upper panel). For example, the number of SWIFD points is arbitrary, and therefore the height of the 'coincident' bar is arbitrary for Alternatives D, A3 and A4. For this reason, we plotted the same data for Alternatives D, A3 and A4 side by side, removing the coincident points to allow for a clearer comparison between those alternatives (**Figure 15**). Results demonstrate that a higher percentage of anadromous data points occurred upstream of Alternative D, while a higher percentage of anadromous data points fell within the modeled AFF for Alternatives A3 and A4.



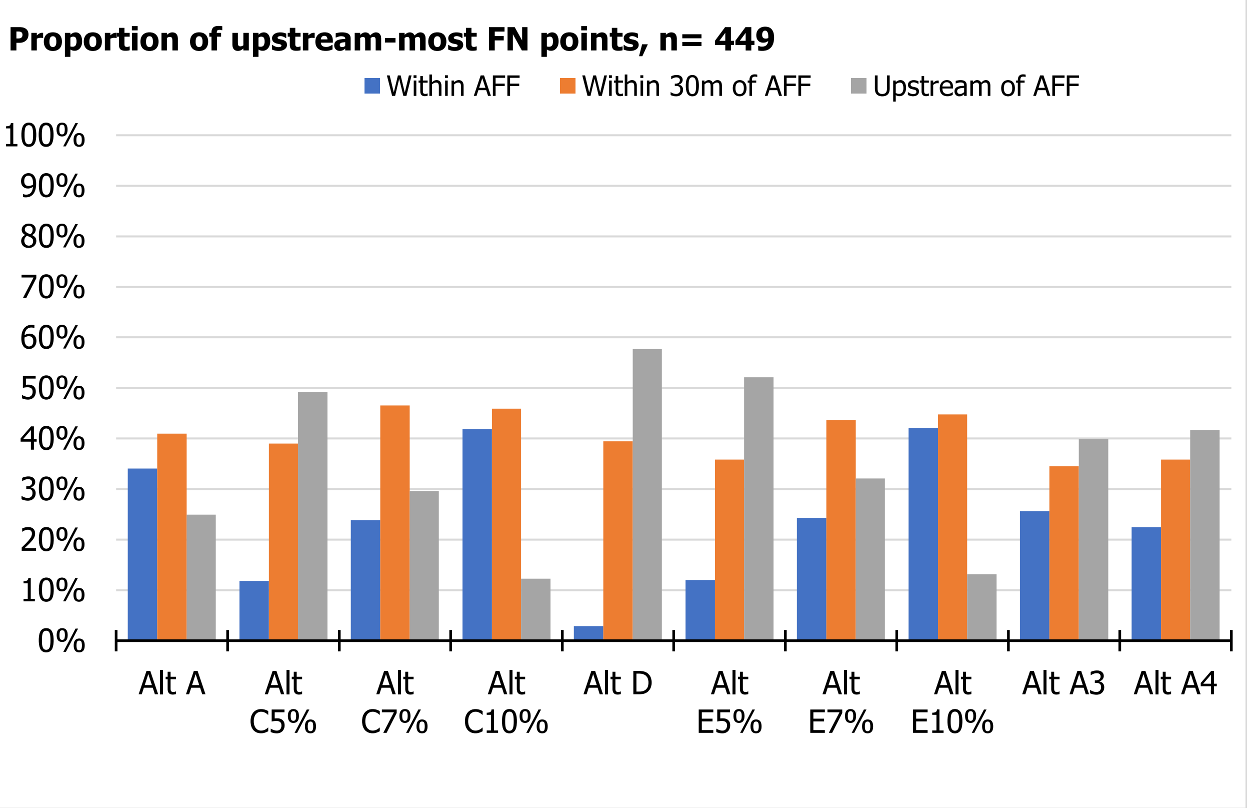


Figure 14. Proportion of all anadromous (SWIFD and other anadromy) and F/N break points observed above, below and coincident with the upper extent of each AFF alternative, for anadromy points (A) and F/N Break points (B). 'Coincident' refers to fish data points located within 30m of channel distance to the AFF termination points. This distance was found to be effectively coincident during the GIS data 'snapping' exercise (see Appendix B).

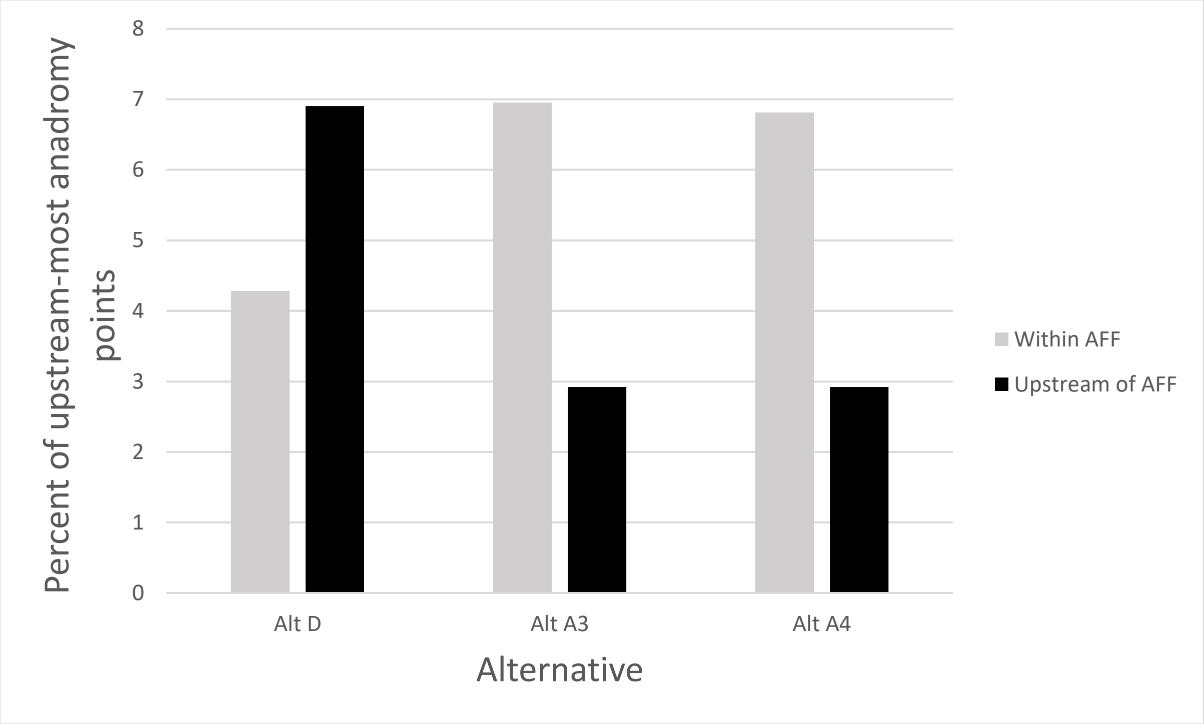


Figure 15. Proportion of upstream most anadromy reference points within and upstream of the modeled AFF for Alternatives D, A3 and A4 with coincident points removed. This exercise essentially removes the SWIFD data from the plot, focusing the results on 'other anadromy' and emphasizing the differences between Alternatives D, A3 and A4 when not compared against SWIFD, which was used in the formulation of the Alternatives.

c. *What is the distribution of maximum channel gradients downstream from known anadromous fish distribution points and concurred F/N breaks?*

The distribution of maximum sustained gradient values downstream from observed or presumed anadromous occurrence and downstream from concurred F/N break points are shown in **Figure 16**. For anadromy, 63% of the maximum values are at 5% sustained gradient or less; 75% have maximum values of 7% or less; and 88% have maximum values of 10% or less. Gradient values above 17% are potential outliers and were removed for this analysis (see discussion). After outliers were removed, a total 650 anadromous fish reference points were used in this analysis.

The concurred F/N break points are typically upstream of the top-most anadromy points and, as expected, have a distinctly steeper distribution of maximum downstream sustained gradient values (**Figure 17, Figure 16**).

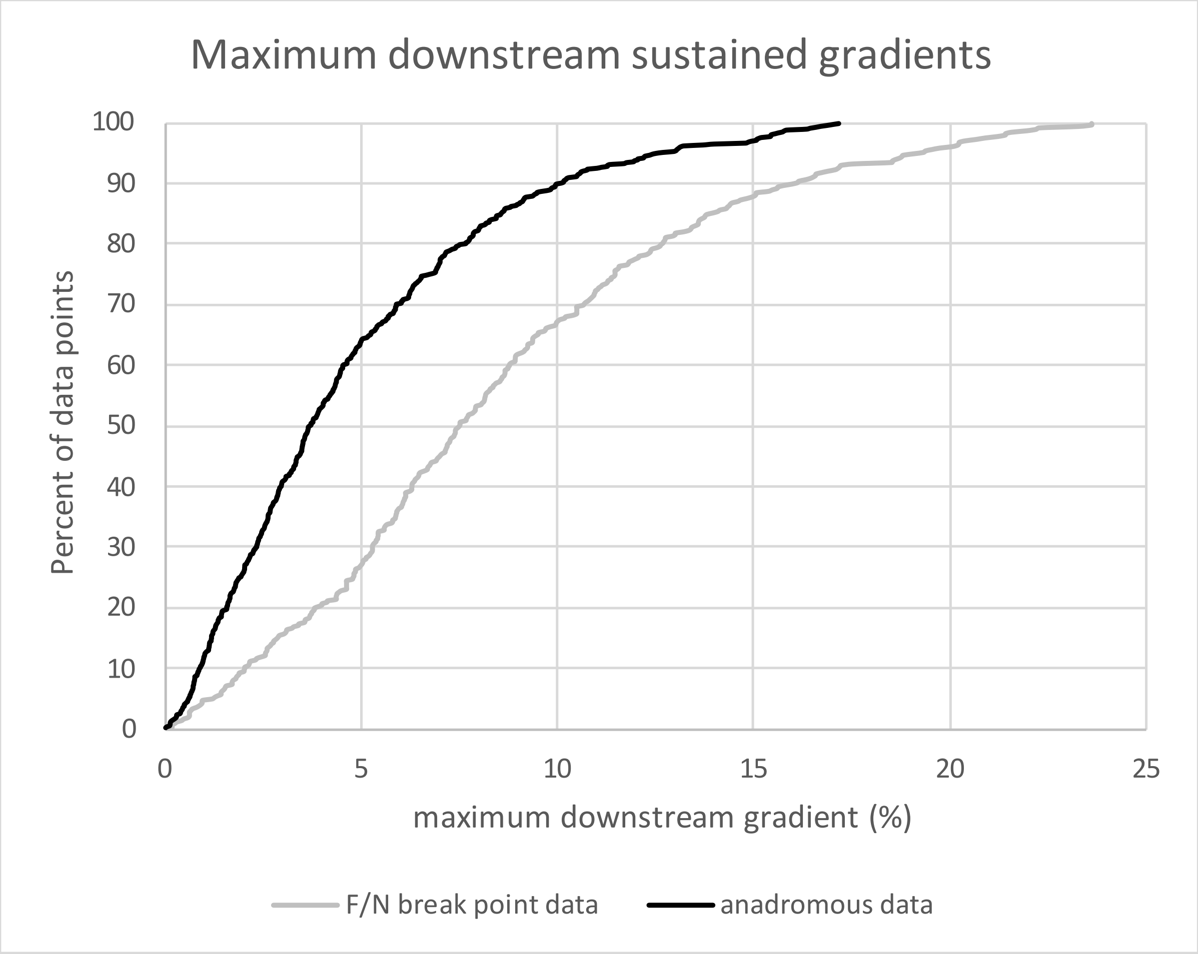


Figure 16. Cumulative distribution of maximum sustained downstream gradient below the observed and presumed anadromous fish data points and F/N break data points in all analyzed basins. Outliers were removed from the plot using the ‘Tukey’s Fences’ metric. In many cases, we discovered these outliers were mis-mapped data points on top of road prisms or other unnaturally steep channel sections.

The steepest downstream gradient from the highest known anadromy points averaged 4.7% gradient (median 3.7%; **Figure 17**). Not surprisingly, when measured from the highest concurred F/N break points the steepest downstream gradient tended to be higher (mean 8.4%, median 7.5%).

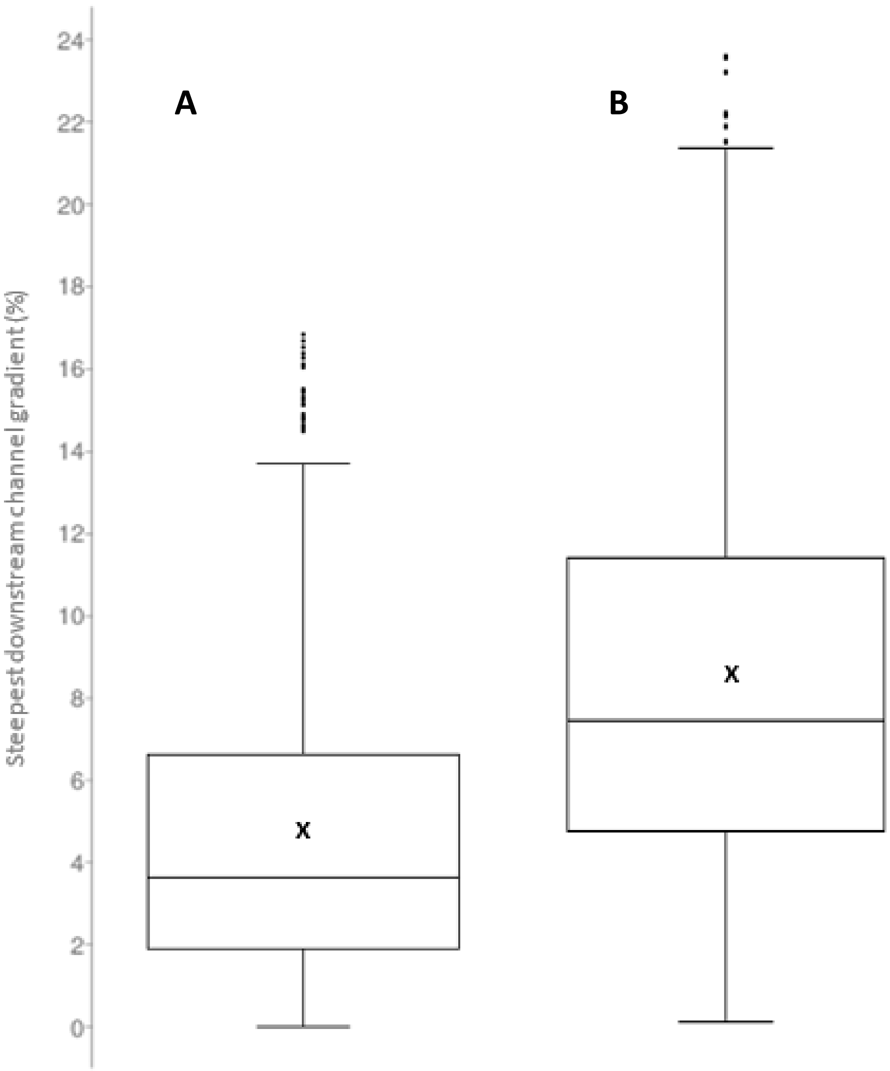


Figure 17. Box and whisker plots displaying the spread of maximum sustained downstream gradients below observed and presumed anadromous points (A) and the concurred F/N break points (B). These are the same data as displayed in Figure 16. The median is indicated by the line in the box, mean is indicated by the 'X', the upper and lower quartiles are shown as the upper and lower box boundaries, respectively, and the range of the trimmed data is shown by the whiskers. Outliers are shown as black dots.

Discussion

The AFF alternatives evaluated by the Project Team consist of two primary approaches to establishing the Anadromous Fish Floor: 1) approaches that rely on gradient thresholds or barriers (whichever is encountered first) upstream from saltwater; and 2) approaches that rely on changes in channel characteristics identified upstream from an 'anadromous core' defined by existing datasets (SWIFD). Alternatives A and E fall into the first category. Alternative A is defined by a sustained gradient threshold (10%) and WDFW-defined permanent natural barriers. Alternative E is based solely on thresholds of sustained gradient (5%, 7% or 10%) that form the ‘anadromous core’ and extend into tributaries. Alternative D falls into the second approach: it is defined by data on known and presumed anadromous fish occurrence plus extensions of the AFF into tributaries using a modified potential habitat breaks framework (ignoring the channel width-based PHB at the core stream-tributary confluence). For Alternative D, the modified PHB framework does not extend beyond the terminal ‘anadromous core’ data point as it does on tributaries connected to the core. Additionally, several alternatives act as combinations of the two primary approaches. Alternative C is a mix of the sustained gradient and ‘anadromous core’ approaches; it uses sustained gradient thresholds (5%, 7% or 10%) to establish the ‘anadromous core’, and the modified PHB scheme from Alternative D to extend beyond the ‘core’ on connected tributaries. Alternatives A3 and A4 use data on known and presumed anadromy to form the ‘anadromous core’ (as in Alternative D) but extend into connected tributaries and above the terminal anadromous data point on trunk streams until a threshold of sustained gradient (10%) or permanent natural barrier is reached.

Discussion of Results

The analyses presented in this report demonstrate that each of these AFF approaches captured most of the stream length defined by known and presumed anadromous fish occurrence data available in the study basins: portions of the modeled AFF that ‘undershot’ the anadromous data (**Figure 10**) or ‘overshot’ the F/N water type break data (**Figure 11**) were small compared to the overall length of each modeled AFF (**Figure 6**).

Clearly, important differences exist between the alternatives that cause them to extend varying distances into the watersheds and above and below the reference fish data. Alternatives that used higher gradient thresholds (A, A3, A4, C10% and E10%) extended the farthest upstream into the watersheds, captured the greatest amount of known and presumed anadromous stream length but tended to overshoot F/N water type breaks by greater distances. Alternative D did not extend AFF classification above known and presumed anadromy in mainstem (terminal) channels.

Alternative D and alternatives that used lower gradient thresholds (C5% and E5%) ended lower in the modeled watersheds, undershot a greater amount of known and presumed anadromous occurrence data (**Figure 10**) and tended to overshoot the F/N water type break locations for shorter distances (**Figure 11**). In the case of Alternative D, the use of known and presumed anadromy to form an anadromous core was an important factor limiting the overall extent of the modeled AFF; this was one reason Alternative D had fewer F/N overshoots (tributaries to mainstems above the terminal SWIFD point were not included). Including an anadromous core in the alternative also prevented the AFF from terminating below waters already identified as anadromous in SWIFD.

The inclusion of barriers in Alternatives A, A3 and A4 reduced the cumulative channel length of those alternatives so they became similar to Alternatives C7% and E7% (**Figure 6**). Incorporating smaller barriers on smaller channels (as is done in Alternative A4) further reduced the total modeled AFF length (**Figure 6**) and the total distance of modeled AFF above the F/N break points (**Figure 11**).

The distribution of maximum sustained gradient values downstream from documented or presumed anadromous occurrence are: 63% of the maximum values are at 5% sustained gradient or less; 75% have maximum values of 7% or less; and 88% have maximum values of 10% or less (**Figure 16, Figure 17**). It is important to consider the following when interpreting the steepest downstream gradient results: as discussed above, the documented and presumed anadromy points used in this analysis do not necessarily represent the upstream extent of anadromy (anadromy likely extends further upstream, and above steeper sustained gradients) and may not capture the full range of anadromy. Similarly, many anadromous data points may be located in floodplain channels that never reach gradients higher than a few percent (i.e. the reason for the end of anadromous habitat is a factor not related to gradient such as the end of the channel, or an obstacle or barrier to upstream movement, not a steep gradient). Therefore, while the steepest downstream gradient results provide some context for the likely range in gradients within anadromous habitat, the true form of the distribution remains unknown.

Streams with 'unknown' fish use

The distance the modeled AFF alternatives extended into streams with no fish data followed the same pattern as the other results: alternatives with larger gradient thresholds extended farther into these streams, and Alternative D and alternatives with smaller gradient thresholds extended less far into these streams. The observed patterns in these streams may indicate what can be expected once a regulatory AFF is implemented. For example, the total distance that the modeled Alternative A extended into unknown fish use streams is nearly twice that of modeled Alternative D (**Figure 6**). If the unknown fish use streams exhibit similar patterns as the streams for which we have fish occurrence data, we can assume that Alternative A will extend beyond the regulatory water type break (F-N) that would have been found under the interim water typing rule in a greater number of cases and for greater lengths of channel. Conversely, we can assume that Alternative D would allow for electrofishing in a greater length of channel that could be expected to host anadromous fish (**Figure 10**).

Uncertainty

The interpretation of the reference fish location data we used in the analysis, and the uncertainty associated with those data, are important to consider in the final evaluation of the modeled AFF alternatives. Below we discuss the major sources of uncertainty associated with the fish distribution data and the modeled channel gradient and stream length estimates, and how that uncertainty can affect interpretation of the results of the spatial analysis.

Uncertainty with anadromy and F/N break points

The anadromous data we used (SWIFD, Squaxin Island Tribe, Skagit-LFA, and USFS) were compiled from pre-existing datasets that were created using different methods. However, all can be interpreted as representing documented or presumed anadromous fish presence (as opposed to presence-absence). We interpret anadromous presence data to indicate locations of observed or presumed anadromous habitat, but do not necessarily represent the upstream extent of anadromous fish or their habitat.

The SWIFD database we used contains approximately 85% of its points in the 'documented' (observed) category, and 15% of its points in the presumed category. The SWIFD 'presumed' data are still anadromous presence data, but there is some unknown amount of uncertainty in the spatial accuracy of these points that we are not able to quantify. This spatial uncertainty could be introduced by extension of presumed habitat beyond documented presence to a permanent natural barrier (where the location of the barrier was uncertain). Therefore, this source of uncertainty likely exists in both directions: presumed anadromous presence may overestimate or underestimate the true anadromous distribution.

In contrast, observed anadromous presence data represent locations of known anadromous fish occurrence but not necessarily anadromous absence upstream. These data, which are represented by >90% of the anadromous points in our dataset (Squaxin Island Tribe, USFS, Skagit-LFA, and ~85% of the SWIFD data), form the basis of our interpretation of the undershoot 'errors' in the modeled AFF alternatives (false negatives). Specifically, where a modeled AFF alternative undershoots a documented anadromous presence point, that length of channel can be safely interpreted as a location where electrofishing would be allowed in anadromous waters under that alternative.

The converse is not necessarily true: where an alternative extends beyond documented anadromous presence data, we do not know whether there is anadromous fish presence upstream from that location because that point does not necessarily represent the upstream extent of anadromy (hence the 'uncertain anadromy' label used in the presentation of the results). For this reason, we relied on the F/N break point location data to inform the interpretation of the 'overshoot' stream lengths (false positives).

The F/N break point data are also composed of a combination of documented and presumed habitat—documented where fish were brought to hand during protocol electrofishing surveys and presumed where the regulatory type break was established and concurred upstream from documented fish at a channel feature believed by the surveyor to represent the likely end of fish habitat. Because these data commonly included the results of electrofishing surveys above the last found fish, they represent the best data we have for reliably determining the absence of fish habitat in the upstream direction.

Our interpretation of 'false positives' is based on this assumption. However, the F/N break point locations contain uncertainty as well; for example, missing fish on single pass electrofishing surveys, seasonal and inter-annual variability in fish distribution, fish presence outside of the seasonal survey window, variable requirements for regulatory acceptance, reduced fish presence and distribution resulting from suppressed population abundance, the proliferation of anthropogenic barriers to fish passage, and degradation of habitat which may be subject to recovery. Conversely, surveyors may extend presumed fish habitat beyond documented presence to a feature believed to represent the likely end of fish habitat. Therefore, this source of uncertainty may exist in both directions: F/N breaks may overestimate or underestimate the true fish habitat distribution.

Significantly, the use of different fish reference datasets to quantify upstream and downstream model performance places limitations on the use of traditional statistical metrics of model fit. For example, we have fewer F/N break point data than SWIFD anadromy data and even fewer 'other anadromy' observations. Because the anadromous data represent anadromous fish presence and presumed presence only, it is difficult to interpret whether errors exist where the modeled AFF alternatives extend beyond anadromous data points. Therefore, metrics such as mean error or sum of errors are difficult to interpret. Moreover, because Alternatives D, A3 and A4 all use SWIFD in their definition, we cannot use SWIFD to compare alternatives where the AFF ends downstream from SWIFD. As a result, comparisons of modeled channel length between alternatives were restricted to within individual graphs presented in the results section to avoid comparing channel lengths computed using different numbers of fish data points.

Uncertainty with modeled channel gradients and stream lengths

The results contained in this report are primarily based on stream gradient measurements conducted using remote data (lidar), but at very high resolution to mimic how a field-based channel unit survey would be conducted. They capture gradient differences between channel units such as pools, riffles, steps, glides and cascades. Further, the gradient threshold approaches used a 'look-ahead distance' method in which sustained gradient was defined as a gradient persisting for a distance equivalent to at least 20 channel widths without falling below the gradient threshold (i.e. lack of 'resting areas'). In practice, this means that field surveyors trying to identify the termination point of an AFF alternative that uses a gradient threshold would need to measure channel gradient over very short channel lengths and ensure that none of these short measured sections fell below the gradient threshold. In practice, it is more common for water type surveyors to measure gradient over a series of step-pool or pool-riffle sequences following a line-of-sight distance. Therefore, it is likely that the method used to measure gradient in the synthetic stream network tends to extend each alternative higher in the stream networks than would be implemented in the field.

Furthermore, the synthetic stream network initiated channels using a combined contributing drainage area and curvature approach based on the elevation values contained within the lidar DEMs. Therefore, uncertainty in the upper extent of the channel network and the number of first order stream channels increase the uncertainty in the total stream length values (potentially affecting the modeled AFF distances into headwater streams). For this reason, we have greater confidence in the relative distances computed for each alternative and less confidence that the absolute distances would be the same as would be implemented in an eventual rule.

Future Field Studies

Potential future field studies could be designed to validate the GIS analysis, improve our understanding of anadromous fish distribution and their habitat associations, and validate the criteria used to define the AFF. Specifically, validation of the GIS analysis could include field surveys of stream gradient, channel width, and barrier / obstacle locations to compare against estimates produced by the TerrainWorks GIS model.

Research could be designed to address gaps in our understanding of anadromous fish presence / absence. For example, interannual and seasonal variability in the distribution of anadromous fish could be addressed through eDNA surveys or targeted electrofishing. Importantly, physical habitat surveys should be combined with fish observations to form a complete picture of anadromous fish associations with habitat characteristics. Similarly, validation of the criteria identified in an AFF rule could be accomplished by the addition of fields on the WTMF for surveyors to identify the locations where anadromous fish are observed and the associated habitat characteristics.

Regardless of the AFF alternative selected, these ideas could be a future focus of adaptive management to validate the results found using the opportunistic data included in this report.

Glossary

Anadromous core – That portion of a stream network encompassed within SWIFD (Alt D, A3, A4) or mainstem streams up to a gradient threshold (Alt C).

Anadromy – A migration form where a fish is born in freshwater, matures in the ocean, and returns to spawn in freshwater.

Concurred_FN, F/N Break – A point on a stream network which results from a concurred water type modification form, representing the upper extent of fish habitat.

False negative – A location where an AFF alternative ended downstream from an anadromous fish reference point (see Figure 2).

False positive – A location where an AFF alternative ended upstream from an F/N reference point (see Figure 2).

Fish Habitat Assessment Methodology (FHAM) - The field survey methodology selected by the WA Forest Practices Board to identify the upper extent of fish habitat; a fundamental component of the long overdue permanent water typing rule.

Gradient Threshold – The point in a channel network where the reach gradient exceeds a target threshold, measured over a minimum distance (20 x bankfull widths, for example).

LiDAR – Light Detection and Ranging – High-resolution elevation data used to generate a digital elevation model.

Look ahead distance – The distance over which stream gradient may not drop below an identified threshold to qualify as a sustained gradient for that threshold.

Other Anadromy – Anadromous fish reference data from sources other than SWIFD: the US Forest Service data, the Squaxin Island Tribe coho data, and the Skagit LFA data.

Other Fish – Point data where resident (non-anadromous) fish were documented.

Permanent natural barrier – A natural stream feature that blocks fish passage and is non-deformable (e.g. bedrock waterfalls and bedrock chutes). This excludes barrier features that may temporarily block fish passage, but that are not permanent (e.g. debris jams, steps, or waterfalls comprised of wood).

Potential habitat break (PHB) – Integral to the FHAM survey methodology, PHBs are stream features with significance to the distribution of fish.

Statewide Integrated Fish Distribution (SWIFD) – A statewide GIS fish distribution (presence) dataset managed by WA Dept. of Fish and Wildlife (statewide) and the NW Indian Fish Commission (western WA).

Sustained gradient – Gradient does not drop below a threshold for a specified distance (see look ahead distance).
Synthetic stream layer – A computer-modeled network of streamlines built using LiDAR to enable estimation of channel characteristics (e.g. gradient, size, obstacles, and barriers).
Uncertain anadromous – Stream reaches above uppermost anadromous fish reference data and below F/N breaks where anadromous fish presence is uncertain.
Water Type Modification Form (WTMF) – A WA DNR form used to propose changes to the regulatory water type map managed by WA DNR.

References

Marks, Olis, Wyman, 2004, An evaluation of the Skagit Basin Coho SSHIAP/LFA database and an assessment of the DNR last fish water type map, Skagit River System Cooperative unpublished report, www.skagitcoop.org/documents/, 6 p.

O'Connor, 2002, Fish distribution and Use Definitions, unpublished report, https://geo.nwifc.org/Docs/SWIFD_Doc/WDFW_FishDistributionandUseDefinitions_2006.pdf.

Appendix A: Schematic comparing Alternatives A3/A4, and Alternative D.

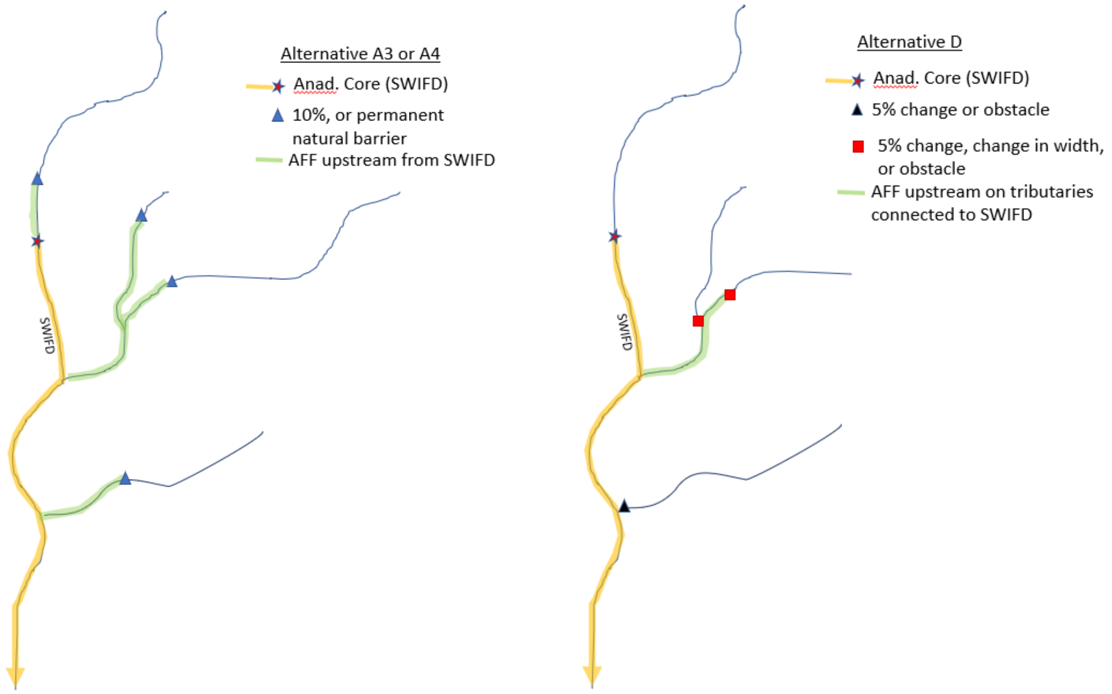


Figure A1. Stream schematic illustrating the difference between Alternatives A3 and A4 (A), and Alternative D (B).

Appendix B: Details of the methods used to construct the synthetic stream network and analyze the AFF proposals

TerrainWorks, August 23 2021

Methods

Field surveys to document fish presence or absence have identified physical stream characteristics associated with the upstream extent of observed fish presence. These include barriers to fish passage, such as waterfalls, and indicators of a change in habitat type and availability, such as changes in channel gradient and stream size. These observations provide guidelines for field identification of the upstream extent of anadromous fish use (Washington Department of Fish and Wildlife, 2019).

Field-survey data have also been used to guide development and calibration of GIS-based models for estimating the upstream extent of fish use (Fransen et al., 2006; McCleary and Hassan, 2008; Walther, 2021). The ability of GIS-based analyses to identify physical stream characteristics depends largely on the resolution and accuracy of available elevation data. Previously available digital elevation data, such as the 1/3-arc-second DEMs available through the National Elevation Dataset (http://ned.usgs.gov/), provided point estimates of elevation at approximately 10-m horizontal grid spacing, sufficient to resolve larger channel courses and channel gradients over tens to hundreds of meters (e.g., Clarke et al., 2008), but insufficient to see physical stream characteristics at the upstream end of most fish distributions.

Recently, however, availability of Lidar-derived DEMs with grid spacings of a meter or less can potentially provide sufficient detail to resolve meter-scale channel features (e.g., Cavalli et al., 2008; Faux et al., 2009; Tompalski et al., 2017; Trevisani et al., 2010). At TerrainWorks, we have been experimenting with techniques to use Lidar DEMs for channel-network extraction (Miller et al., 2015) and characterization of watershed and channel characteristics for habitat assessment (Romey, 2018), including development of algorithms for identifying barriers to fish passage (waterfalls and obstacles) and for measuring channel gradient over a range of length scales. We are using these techniques for this project with Lidar DEMs for a select set of Watershed Administrative Units in Washington State to assess different approaches for GIS-based delineation of an anadromous fish floor.

A Synthetic Channel Network

An important factor for enabling a computer-based analysis of channel profiles is the type of digital representation used to characterize channels. A DEM provides point estimates of ground surface elevation over a horizontal grid. Topographic attributes derived from these elevation points are used to delineate the stream-channel network and to estimate flow paths for surface and shallow subsurface water to and through that network. In a GIS, channel networks are represented as a set of lines with intersections at channel confluences. In our software, channels are represented as a set of linked nodes. Each node is associated with a DEM grid point and has a set of attributes that describe conditions at the node location. Each node is linked to the adjacent upstream and downstream nodes, so that flow paths can be traced through the network both up and downstream. The set of attributes assigned to each node is determined by the analyses being performed and may include characteristics of the channel, of the adjacent floodplain and riparian zone, and of the upstream contributing area (Barquin et al., 2015; Benda et al., 2007). For our purposes here, the information maintained at each node includes elevation and flow distance from the basin outlet, which we can use to estimate channel gradient and to identify features along the channel profile such as water falls and steep channel sections that may indicate bedrock shoots or boulder cascades. We also determine the contributing area and mean annual precipitation over that contributing area for each node. These values are used in regional regression equations to estimate the channel width and depth at each node.

We use this linked-node data structure because it allows us to maintain information at the spatial grain of the underlying DEM, which is essential for resolving channel features, like waterfalls, at length scales relevant for identifying potential barriers to fish. The node-based information can be summarized and output to common vector-file formats that can be read by a GIS such as ArcInfo.

Field survey data

The AFF project team assembled survey data from a variety of sources. The providence of these data are described in the previous section; here we describe relevant aspects of these data. These data represent conditions associated with a specific location on a channel. These point data were assembled by the AFF project team into an Arc Info geodatabase that provided both the ground location and a table of attributes associated with each point. Data points were associated with observed barriers and fish presence or absence.

Although each point was associated with a specific location on a channel, the digitized locations did not generally fall directly on a DEM-traced flow path in the synthetic channel network. These discrepancies arise from a variety of causes. Ground-point locations may be determined from GPS coordinates, which depending on the instruments and methods used, may have precision of only 10 meters or less, or are inferred from base maps, such as the USGS 1:24,000-scale topographic maps. These locations may then be aligned with an existing digital stream layer when brought into a GIS, such as that maintained by the Washington Department of Natural Resources[3]. The DNR stream layer was constructed without high-resolution elevation data and the channel courses do not generally align exactly with those determined by tracing flow paths through a Lidar DEM, with discrepancies in places of tens of meters. Hence, we need to move (in GIS terminology: snap) the data point locations to fall on flow paths in the synthetic channel network. Given the more than 10,000 points in this database for the study basins, we used an automated procedure to do so, with subsequent visual checks. For each point in the database, we used an automated procedure to look for the closest channel node in the synthetic network within a 100-meter radius. If any road crossings of a synthetic channel fell within this search radius, the point was snapped to the closest road crossing, assuming that the observation was made at the crossing, e.g., at a culvert.

The project team then visually reviewed the snapped point locations to identify those clearly snapped to the wrong location. This may occur, for example, where a data point should lie on a tributary to a larger channel but was snapped to the larger channel. Review of the dataset also identified a number of SWIFD points located considerably further upstream than seemed appropriate. These points were associated with "No_Gradient_Barrier" entries in the "Fish_Habitat_data_type" field of the attribute table for the project database and were excluded from further analyses.

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[3] https://data-wadnr.opendata.arcgis.com/datasets/wadnr::dnr-hydrography-watercourses-forest-practices-regulation/about

Web-Based Map

To aid with ongoing project-team review of the data products and analyses, the synthetic channel networks and AFF-project database points were uploaded to a web-based map viewable in a web browser. Different symbols and colors were used to distinguish different types of data points. These included observations of fish presence, documented points of upstream fish extent (concurred F/N break points), and barriers. The upstream-most fish points were flagged. Channels in the synthetic network were divided into reaches based on modeled channel gradient and color coded to indicate extent of the modeled AFF. Points indicating modeled barriers and potential habitat breaks were also displayed. The map interface allowed users to move around the map and to zoom in or out and to toggle each layer on and off.

With this map, AFF-project-team members were able to review data products and identify errors in the database and synthetic networks. This is a daunting and time-consuming task; the original AFF-project dataset had nearly 12,000 data points. Corrections included: moving of data points to correct their location, removal of some data points, addition of channels to the synthetic network, repositioning of some channels, and removal of some traced channels.

Channel Classification

Points in the database associated with fish presence or absence were used to divide channels in the synthetic network into classes reflecting the potential for fish use. The database included a field Life_History with the following five entries:

1. SWIFD_Anadromy: Locations in the Statewide Integrated Fish Distribution (SWIFD) database indicating presence of anadromous fish.
2. Other_Anadromy: Data sources other than SWIFD indicating presence of anadromous fish.
3. Resident: Resident fish use.
4. Unknown_Life_History_type: Use by fish of unknown life history type.
5. Concurred_FN: Concurred F (fish bearing) to N (non-fish-bearing) water type location.

With these we defined 8 channel classes:

1. SWIFD Anadromous. Continuous downstream from the upstream-most SWIFD_Anadromy point.
2. Other Anadromous. Continuous downstream from the upstream-most Other_Anadromy point until a SWIFD_Anadromy point is encountered. SWIFD_Anadromy takes precedence.
3. Concurred resident fish use. From a Concurred_FN point downstream until an anadromy point is encountered.
4. Resident fish use. From top-most resident point until an anadromous point is encountered, applies to channels with no Concurred_FN point.
5. Concurred unknown life-history fish use. If a Life_History_Unknown point lies downstream of a Concurred_FN point, the channel from Concurred_FN to the first encountered resident or anadromous point is classified as Concurred unknown life history fish use.
6. Unknown life history fish use. From the top-most Life_History_Unknown point until a resident or anadromous point is encountered.
7. Verified no fish. Upstream of a Concurred_FN point.
8. No data. Upstream of top-most fish point for channels lacking a Concurred_FN point.

All channels within the synthetic network fell within one of these eight classes. The modeled extent of the AFF can be overlain on these channel classes. The length of the AFF within each class will be used to evaluate the performance of the modeled AFF.

Rules for determining the upstream extent of the anadromous fish floor

Recall that: “The upper extent of the AFF will be determined by measurable physical stream characteristics, downstream from which anadromous fish habitat will be presumed”. Of the many possible sets of physical stream characteristics that could be used for determining the AFF, the AFF team has identified four alternatives, listed in Table 1. Alternatives A, C, and E require determination of “sustained” gradients; Alternative A requires identification of permanent natural barriers (as defined by Washington Department of Fish and Wildlife, 2019); Alternatives C and D require identification of permanent natural obstacles as defined the Landowner Proposal. I outline each of these in more detail below and describe the methods used to identify each.

Table 3. Alternatives definitions for the AFF

Alternative A[1]	Alternative C[1]	Alternative D[2]	Alternative E[3]
Waters within the anadromous fish floor. These are waters connected to saltwater and extending upstream to a *sustained 10% gradient* or a permanent natural barrier, whichever comes first. These waters contain main stem stream segments and associated tributaries.	Waters within the anadromous fish floor. These are waters connected to saltwater that have a *sustained gradient of 5% [or 7% or 10%]* or less, and include associated *tributaries lacking a 5% gradient increase* or permanent natural obstacle at the junction with the main stem.	Waters within the anadromous fish floor. These are waters connected to saltwater that are included in widely available GIS datasets of known and presumed anadromous use (such as SWIFD or StreamNet), and include associated *tributaries lacking a 5% gradient increase* or permanent natural obstacle at the junction with the main stem.	Waters within the anadromous fish floor. These are waters connected to saltwater and extending to a *sustained 5% or [7% or 10%] gradient*. These waters contain main stem stream segments and associated tributaries.

Table taken from an April 14, 2021 memo from the Anadromous Fish Floor Project Team to the Forest Practices Board's Water Typing Rule Committee.

[1] Language accepted by the FP Board at the May 2019 Board meeting.

[2] Language crafted by AFF Project Team to reflect the AFF proposal as explained by the large landowner caucus in April 2021.

[3] Language crafted by the project team. This alternative includes the 5%, 7%, or 10% component of alternative C, but does not include the natural barrier component of alternative A or the 5% gradient increase component of alternative D.

Determination of channel gradient

Channel Profile

We want to measure channel gradient using the DEM-traced channel profiles in a manner consistent with the way that gradient is measured in a field survey. In a field survey, the surveyor typically measures the horizontal (or slope) distance and elevation difference (or slope) between two points along the channel. These points are referred to as survey stations and the distance between stations is set by the types of features the surveyor seeks to identify and by the distance along the channel with a clear line of sight. Typically, survey stations are placed at the end points of different channel units (pools, riffles), which are commonly associated with a change in gradient. We can try to replicate this procedure with the channel nodes along a DEM-traced profile. I want to establish “stations” at nodes along the profile where there is a distinct change in gradient. I also want to specify a minimum distance between stations and the level of degree to which changes in gradient are recognized. I do not want a series of 1-m reaches or reaches that hug every tiny variation along the profile – neither would reflect the way that an actual ground-based survey is conducted.

To identify locations in the channel profile where there are changes in gradient, I developed the following procedure.

1. Ensure that all DEM channel profiles are monotonically decreasing in elevation downstream. For small channels in particular, noise in the DEM and the lack of elevation information between grid points[4] can result in short uphill sections moving downstream. These are all flattened out, assuming that the higher points reflect lidar reflections from riparian vegetation or channel banks.
2. Specify a minimum reach length: all reaches should be as long as or longer than the specified minimum value. This value may scale with channel size; e.g., as a specified number of channel widths.
3. At each node, find the upstream node closest to the specified distance along the flow path. Likewise, find the downstream node closest to the specified distance. The upstream-looking and downstream-looking gradient at the node is then calculated from the change in elevation between the nodes. The change in gradient at the node is the difference between the upstream-looking and downstream-looking gradients. Do this for every channel node.
4. Rank the change-in-gradient values for all nodes from largest to smallest.
5. Take the node with the largest change-in-gradient value; this node represents a location for a survey station. Set all other change-in-gradient values for nodes within the specified distance up and downstream to zero, thus precluding placement of an adjacent survey station within the minimum specified reach length.
6. Of all the remaining nodes, go the one with the largest change-in-gradient value and repeat step 4. Repeat steps 4 and 5 until all nodes have either been identified as a survey station point or had their change-in-gradient value set to zero.

The flagged channel nodes now provide a series of stations along a channel profile placed where there are distinct changes in gradient and with none closer to each other than the specified separation length. The channel profile is then approximated as a piece-wise continuous linear profile with straight line segments extending from station to station.

These concepts are illustrated for a portion of a channel profile in Figure 2. Each small circle indicates the location of a channel node along the DEM-traced profile and the straight-line segments connecting the large open circles indicate the piece-wise linear profile fit to the DEM points as described above. The degree of detail maintained in the fit profile decreases as the measurement length for gradient increases. Shorter measurement lengths resolve short steep channel segments that get smoothed out with longer measurement lengths.

The elevation difference between the straight-line segments in this modeled profile and the channel nodes is also tracked. To ensure that the modeled profile includes the desired degree of detail, we can

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[4] DEM grid points have a 1-meter horizontal spacing. Along a small channel, some points may fall within the channel and some on the banks. A profile based on these may bounce around between channel and channel-bank elevations.

place additional stations where this discrepancy exceeds some specified elevation difference. This option allows channel segments shorter than the specified minimum length, but in exchange, ensures that the desired level of detail in the channel profile is maintained. This is illustrated in Figure 3, where a maximum elevation discrepancy of 0.2 meters was enforced.

The piece-wise linear profile fit to the DEM-traced channel-node profile can potentially provide a measure of channel gradient and changes in gradient consistent with field-surveyed channel profiles. The degree of consistency between a DEM-derived profile and a field surveyed profile will depend in part on the precision of measured distances and elevation changes in both profiles, on the resolution of the DEM, and on the amount of noise in the DEM. Figure 4 shows a comparison of DEM-derived and field-surveyed gradients along a portion of a channel profile.

Geo-referencing of a ground-based survey to a DEM is quite challenging. The precision to which ground-based station locations can be placed on a DEM, even with GPS readings, is several meters or more – the same length scale as a channel unit. Measures of distance on the ground-based survey and the DEM-traced channel vary along the profile. We should not, therefore, expect longitudinal changes in gradient to match up precisely between field-surveyed and DEM-derived profiles. In Figure 4, although the locations of individual channel units indicated by changes in gradient do not align well, the magnitude and length scale of variability of the two profiles are similar, at least for this case. This example indicates that a DEM-derived channel profile can accurately indicate longitudinal changes in gradient consistent with those measured with field surveys.

Look-Ahead Distance

It is encouraging to find that we can see changes in channel gradient with a DEM-derived profile at a high level of detail, potentially consistent with a ground-based channel-unit survey. Gradient is a factor determining channel-unit type (Montgomery and Buffington, 1997; Rosgen, 1994), so measures of gradient provide indicators of the type and abundance of aquatic habitat that likely exist over a channel segment. A "sustained" channel gradient exceeding some threshold level is used as an indicator of the upstream extent of potential fish presence in three of the four alternatives for determining extent of the AFF and recognized as an indicator of fish extent by the Washington Department of Fish and Wildlife (2019). Our task now is to determine the channel length over which gradient and changes in gradient provide a useful indicator of the potential for finding fish – how to measure a "sustained" gradient. Note that this is separate from identifying physical barriers to fish passage, such as waterfalls, which I address later. Gradient is more ambiguous. Imagine two 100-meter reaches in a 3-meter-wide channel, both with an average gradient of 15%, one of which has no channel units with gradient less than 12% or greater than 18%, while the other has segments exceeding 20% but also segments with gradient less than 5%. Both reaches have average gradients consistent with a cascade channel, but the reach with the low-gradient segments may offer a sequence of step-pools that the other reach lacks, and thereby provide habitat essential for fish use unavailable in the other 100-meter reach (see also section 7.2 in Washington Department of Fish and Wildlife, 2019). We want to look not just at maximum gradients or average gradients, but at the range of channel gradients available. Our task now is to determine the distance over which that range of gradients is important to fish.

To do that, we can specify a "look-ahead" distance over which gradients along the channel profile are examined. For our purposes, this look-ahead distance defines the length over which a threshold gradient must be sustained. For each channel node, the minimum sustained gradient is the lowest gradient encountered along the channel profile within the look-ahead distance upstream of the node. This concept is illustrated in Figure 5. The "channel-unit" gradients are measured from the piece-wise linear profile fit to the DEM-traced channel node profile. The minimum sustained gradient is then defined as the minimum channel-unit gradient found withing 20 channel widths upstream.

Note that in Figure 5, I used a look-ahead distance scaled by channel width. We can specify a look-ahead distance either as a fixed length or as a function of some measure of channel size. It seems logical to vary this length with channel size: a pool in a 1-meter-wide channel will not likely persist over the same channel length as a pool in a 30-meter-wide channel, but we will examine results using both methods for specifying the look-ahead distance.

To examine the effect of the specified look-ahead distance, we used measures of sustained gradient obtained over a range of fixed and variable-length look-ahead distances to delineate the anadromous fish floor using the alternatives presented previously. The resulting AFF was then overlain on the channel types defined using the observations of fish presence or absence presented previously. Two cases can be used to gauge performance of a look-ahead distance:

1) Where observed anadromy extends upstream of the delineated AFF. This is a "false negative".
2) Where the AFF extends upstream of concurred F/N break points into channels classified as "verified no fish". This is a "false positive".

Because we are seeking an anadromous *floor*, "downstream from which anadromous fish habitat will be presumed", false negatives are not necessarily bad – we would like to keep the false-negative channel length as small as possible, but we can anticipate some length of false negatives – but we want to avoid false positives.

Barriers and Potential Habitat Breaks

Alternatives A, C, and E use a threshold in sustained gradient as one criterion for determining the upstream extent of the modeled AFF. The sustained gradient provides an indicator of potential habitat type – or lack of habitat – that serves as a gauge of potential fish presence. Physical barriers can also act to preclude upstream fish presence. The Washington Fish and Wildlife Fish Passage Inventory, Assessment and Prioritization Manual (2019) identifies two types of natural barriers:

1. Gradient, defined as a reach with sustained gradient ≥ 20% for ≥ 160 meters without resting areas.
2. Waterfall, defined as a single, near vertical drop > 3.7 meters in height.

For Alternative A, in addition to the 10% sustained gradient threshold, these two types of barriers are used to identify the upstream extent of the AFF where they are encountered downstream of the sustained gradient threshold.

The WDFW definitions do not incorporate channel size into these barrier definitions. It seems plausible that the ability of fish to traverse a potential barrier might vary with channel size, so the AFF-project team devised an alternative channel-width-dependent set of barrier criteria (Barrier Definition for Anadromous Fish Floor GIS Analysis, memo dated 03/29/2021):

1. Gradient:
    a. Channels < 5 feet in width: sustained gradient ≥ 20% for ≥ 100 feet (30 meters)
    b. Channels 5 – 10 feet in width: sustained gradient ≥ 20% for ≥ 250 feet (76 meters)
    c. Channels > 10 feet in width: sustained gradient ≥ 20% for ≥ 515 feet (160 meters)

2. Waterfall:
    a. Channels < 5 feet in width: near vertical drop ≥ 5 feet in height (1.5 meters)
    b. Channels 5 – 10 feet in width: near vertical drop ≥ 8 feet in height (2.5 meters)
    c. Channels > 10 feet in width: near vertical drop ≥ 12 feet in height (3.7 meters)

These along with the 10% sustained gradient threshold are referred to as Alternative A2.

Alternatives C and D rely on an "anadromous core", within which anadromy is assumed, and then extend the AFF upstream on tributaries to the anadromous core until a barrier or potential habitat break is encountered. Two types of potential barriers are defined:

1. Vertical step ≥ 3 feet (0.9 meters)
2. A sustained gradient of ≥ 20% that persists for a sufficient length so that the elevation increase along the segment is ≥ one channel width. These are referred to as nonvertical obstacles (NVO).

Two types of potential habitat breaks are defined:

1. A gradient break, identified as a point along the channel profile where the upstream-looking gradient exceeds the downstream-looking gradient by 5% or more for at least 20 channel widths.
2. A decrease in channel size at tributary junctions of 20% or more. We use the modeled channel width as an indicator of channel size.