Stream Gradient and Anadromous Fish Use Analysis

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Summary

- The westside tribes have proposed to the Washington Forest Practices Board the inclusion of a gradient-based threshold below which streams are presumed to contain fish (anadromous floor) as part of the current water typing rule-making effort. However, there are few studies that specifically inform the relationship between stream gradients and anadromous fish distributions in western Washington. This analysis demonstrates a potential way to empirically address that data gap.
- Reach gradients in 30 meter fixed-length segments in Skagit and Samish river basins streams were measured downstream from 387 Coho distribution points for five kilometers to quantify the steepest slopes Coho traversed to reach those points.
- For the 91 Coho points observed with natural barriers as the termination of distribution, the median of the steepest downstream gradient was 9.2%. We present a range of percentiles in the Results section.
- These methods and analysis can be replicated in other watersheds to expand our understanding of the relationship between stream gradients and anadromous fish distributions.

Introduction—*Framing the Context for this Analysis*

The level of protection (buffer width) forest land riparian areas receive under Washington State's forest practice rules depends on whether the associated stream is fish bearing or non-fish bearing. The current system of determining whether a stream is fish bearing relies on protocols that allow for single-pass sampling of fish presence. Washington State is in the process of updating this system to accurately identify and protect fish habitat, but this new proposal also relies on single-pass sampling. [1] There are concerns that a one-time sampling protocol biases against identifying fish bearing streams for a variety of reasons, including seasonal and inter-annual variability of fish use and distribution within watersheds, local extirpation due to environmental and human-caused disturbance, environmental variability such as large floods or drought conditions, and/or density dependent factors and recent population depression that can lead to 'false-negative' results. A single pass protocol may not account for streams and fish

[1] The new system utilizes Potential Habitat Breaks (PHBs), which are combinations of stream characteristic (width, gradient, obstacle) that indicate a potential end of upstream fish passage. These points identify where to begin surveys for fish presence/absence when determining fish use, and where to locate the type F and N breaks if fish are not observed. An additional concern is that by adopting PHB definitions as 'rule' instead of board manual guidance, as the DNR is currently recommending, makes it a lot more difficult to deviate from those criteria because of legal implications regardless of site-specific conditions and situations.

stocks in forest lands that are currently degraded but which over time are expected to recover and provide for the opportunity of expanding fish distribution to reaches that may not currently support fish.

An additional concern is that one of the goals of the new water typing system is to reduce electro-shocking in anadromous waters in order to protect ESA listed fish and fish habitat. It is not clear to what extent the new system will succeed at that goal given the continued reliance on fish presence to identify fish habitat.

To help address these concerns, the westside tribes proposed to the Forest Practices Board (Board) at their February 14, 2018 meeting that new stream typing rules being considered include a gradient-based 'anadromous floor.' Under that proposal, streams within the anadromous floor (i.e., below a stream gradient threshold) are presumed fish habitat unless a natural permanent barrier prevents upward movement of fish. Once above the gradient threshold, or above a natural permanent barrier, whichever is lower in the stream network, a stream may be typed as either fish or non-fish according to an appropriate survey. The tribes proposed that the anadromous floor be based on a 10% stream gradient threshold. At that February 14 meeting the Board accepted the tribe's anadromous floor proposal for consideration in the ongoing rule making process. The Board also voted to include anadromous floor proposals based on 5% and 7% gradient thresholds for consideration.

Problem Statement

Currently there are few published studies or sets of findings that specifically and empirically quantify the relationship between stream gradient and likelihood of anadromous fish access and passage in Washington State. Anadromous fish navigate a wide range of stream gradients, but the frequency distribution and the range of those gradients have not been systematically quantified. Washington State's Adaptive Management Program relies on data and findings from research and monitoring projects to guide rule changes. The anadromous floor proposals currently do not have specific data, analyses, or study findings that directly and empirically inform the definition of an anadromous floor. In this report we address this data gap using lidar-based longitudinal profiles and GIS spatial analyses downstream of known and presumed Coho observations. This report provides the Adaptive Management Program and the Board with an example of an analytical approach that can directly inform the establishment of a gradient-based, empirically supported anadromous floor for adoption into rule.

Objectives

- Describe how anadromous fish distributions relate to stream gradient in the Skagit and Samish river basins.
- Provide information that can be used to determine a stream gradient threshold that defines presumed anadromous fish use.

Questions of Interest

1. What is the distribution of gradients anadromous fish utilize or are able to traverse in western Washington streams that are not blocked by artificial barriers?
2. How does the likelihood of anadromous fish access and navigation through a stream reach change with gradient?
3. Does the analysis described in this report successfully characterize and quantify the relationship between stream gradient and anadromous fish use and can it be replicated in other watersheds?

Methods

<u>Data</u>

The Skagit River System Cooperative (SRSC) used existing data from the Salmon and Steelhead Habitat Inventory and Assessment Program (SSHIAP) to summarize anadromous fish distribution within the Skagit and Samish River basins (Fig. 1). SSHIAP is operated jointly by the Washington Department of Fish and Wildlife (WDFW) and the Northwest Indian Fisheries Commission (NWIFC). This program manages a spatial database that characterizes salmonid habitat conditions and distribution for Washington salmonid stocks. In the Skagit and Samish River basins, salmon distribution was assessed through a technical advisory group (TAG) where local fish biologists convened to provide points of known salmon distribution which aided the habitat limiting factors analysis for WRIA's 3 and 4.

Although this dataset contains fish distribution information for all salmon and steelhead stocks, we used a combination of observed and presumed Coho distribution points (approximately 80% observed, 20% presumed). Coho salmon use is widespread across the landscape, they tend to extend the furthest upstream compared to other salmon species, and their habitat use is well understood. Furthermore, SRSC ground-truthed a sample of this dataset for the Skagit/Samish River basins and determined that 97.5% of the sample were field verified to have Coho present or to be Coho habitat (Marks et al., 2004).

The total number of Coho distribution points available in the Skagit and Samish River basins is 519 points. These points were plotted in a GIS along with a Digital Elevation Model – derived hillshade image from the 2016 North Puget and 2015 Glacier Peak lidar acquisitions. In cases where an adjacent channel was clearly the intended target for the Coho distribution point, that point was manually moved to coincide with the channel. In cases where there was no nearby channel to move the Coho point to, those points were eliminated from further consideration in the analysis because the GIS analysis would not work without a channel present. After running the analysis we noticed two outliers with maximum gradients of 60% and 70%, respectively. We removed these points due to the lack of confidence that Coho would be found at these gradients and because they were separated from the next highest slope by ~25% gradient. This reduced the total number of Coho distribution points used for analysis to 387 points.

A degree of variability was discovered in where Coho points were placed on streams by fish biologists during the original data collection portion of the TAG meetings. Some biologists placed points at fish blocking culverts, others at natural barriers, some at the end of the stream channels (e.g., floodplain channels), and some were placed along mid-channel reaches, well short of the end of perceived Coho access. We attributed these locations in our analysis so that the data could categorized. We used several SRSC in-house datasets to help with this sorting process. The SRSC Culvert Inventory was used to attribute Coho points that were placed on a fish blocking culvert. For attributing the Natural Barrier field in the GIS we used the SRSC Natural Barrier Inventory, WDFW Off-Channel Habitat Inventory, DNR Water Type Modification survey reports, and personal knowledge. The following table describes the natural barrier designations that were used in our point-by-point sorting process.

Table 1. Description of the natural barrier categories.

Natural Barrier	**Description**
Yes	Coho distribution point was placed at a confirmed natural barrier.
No	Coho distribution point was placed downstream of a natural barrier and not at any specific in-channel feature.
Unknown	Coho distribution point was placed near an unconfirmed natural barrier.
End of Channel	Coho distribution point was placed at the end of the stream channel; these sites were mostly found in the floodplain of a river or large stream.

Natural Barrier = Yes: This category has points that were placed at the end of known Coho use and were associated with a confirmed barrier. These barriers are a mixture of falls and steep cascades that were confirmed by an in-house dataset or personal knowledge.

Natural Barrier = No: These points were placed in a stream where Coho salmon were observed and are downstream of any natural barrier. There are no in-channel features associated with these locations.

Natural Barrier = Unknown. The points in this category were placed near a natural barrier, but the natural barrier status has not been confirmed in the field or by any of the consulted barrier databases.

Natural Barrier = End of Channel: These points were placed at the end of the stream channel with no channel present upstream. Most of these points are found on lower gradient channels on the floodplain of a larger stream or river and are groundwater/spring fed in nature.

It is important to understand the biases introduced with each of the above categories. By bias we mean each of the categories contains a portion of the dataset representing a different interpretation of Coho distribution across the landscape; each category may contain a skewed distribution of channel gradients with respect to each other category due to the physical setting it represents. Because one or more of the above bins may be more useful for defining an anadromous floor than the others, and because the number of points in each bin varies, the dataset overall should also be regarded as containing bias. Care should be exercised when interpreting the channel gradient results with respect to each bin. We discuss the biases inherent to each of the bins in the Discussion and Recommendations section.

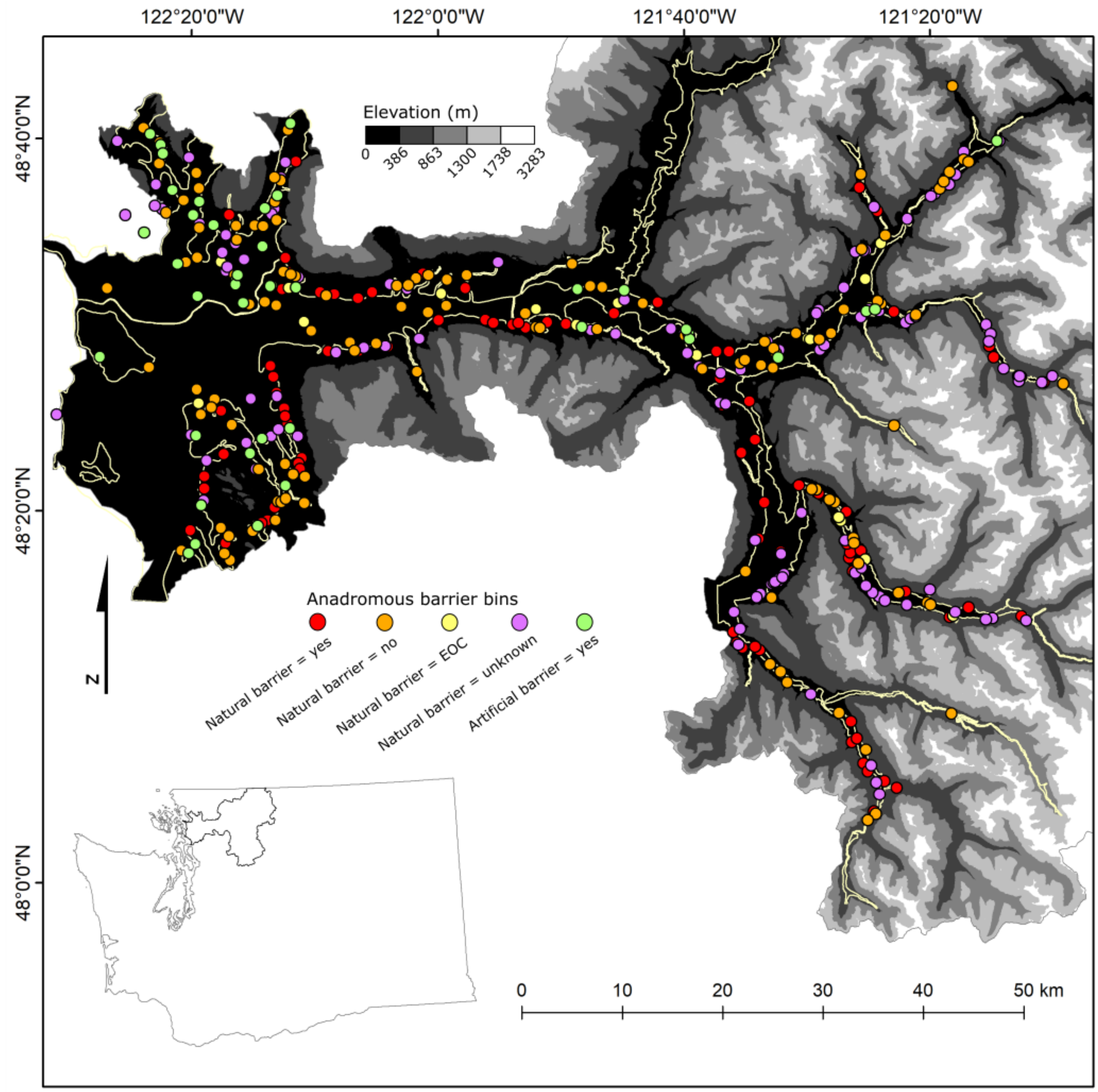

Figure 1. Location map of the Skagit and Samish River basins. Contours of elevation are shown in grayscale. The Coho observation points from the SSHIAP database used in this study are shown with colors representing the barrier categories. A previously-generated anadromous distribution polygon (yellow outline) is also shown (Beamer et al., 2000). Inset shows location in northwestern Washington State.

Measuring downstream gradients

The goal of this step of the analysis was to quantify the maximum slope traversed by fish downstream of each Coho observation point. We highlight the maximum downstream gradients because these represents the range of the gradients Coho successfully traversed, based on the assumption that all gradients below these maximum gradients can be successfully traversed. We summarize the method here and present details in the appendix. Our GIS method involved a combination of work in a desktop GIS program (ArcGIS 10.5) and automated programs written in the python (2.7) programing language. We conducted the bulk of the analysis in python and used ArcGIS to analyze the results and detect potential sources of error that could be addressed in subsequent python runs. Using the Geospatial Data Abstraction Library (GDAL) within python, we extracted channel thalweg pixels from a bare earth lidar digital elevation model (DEM) for 5 km of stream length downstream of each point. Next, we measured channel gradient between the endpoints of each 30 m reach within the 5 km segment by a simple rise / run calculation. We appended the maximum gradient from the set of 30 m reaches onto the original Coho distribution point locations. Additionally, we created GIS files showing the location of the channels identified by the algorithm for each point, as well as the X-Y coordinates of the 30 m reach that contributed the maximum slope within each 5 km segment. We used the latter two datasets for troubleshooting and refining the method.

Results

Figure 2 displays the locations of the Coho distribution points sorted by gradient categories. As seen in the figure, the low gradient points are predominately in the valley bottoms. The higher gradient points tend to be located near the edges of a previously-generated anadromous distribution polygon (yellow outline) (Beamer et al., 2000).

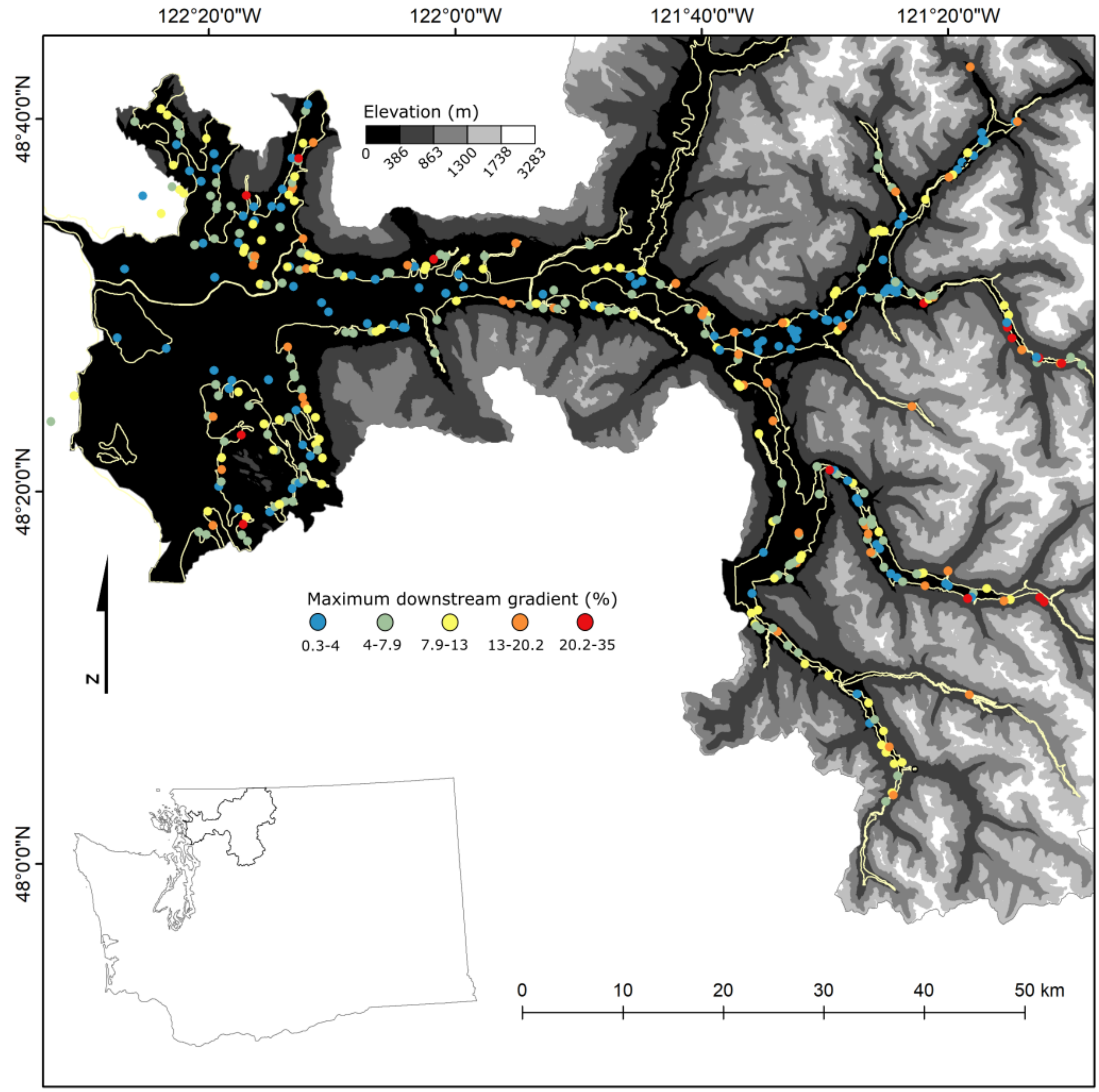

Figure 2. Location map of the Skagit and Samish River basins. Contours of elevation are shown in grayscale. The Coho observation points from the SSHIAP database used in this study are shown with colors representing the maximum downstream gradient. A previously-generated anadromous distribution polygon (yellow outline) is also shown (Beamer et al., 2000). Inset shows location in northwestern Washington State.

Preliminary results of the GIS analysis are presented in figure 3 and summarized in Table 2. In Figure 3 each panel shows a different barrier category (all points, points below natural barriers, points not below natural barriers, points at the end of channel, natural barrier status unknown, and points below artificial barriers). For all combined Coho distribution points (n=387), the median maximum downstream gradient was 6.4%. Natural barrier points (n=91) had the highest median downstream slope (9.24%), approximately 3% higher than the median of all points used. Points not below natural barriers (n=119) and points at end of channel locations (n=23) had lower median steepest downstream gradients (4.73% and 2.65%, respectively). This is expected because these points were not associated with the uppermost extent of Coho habitat in the channel network (i.e. in the case of the 'natural barrier = no' category there may be steeper—but still passable—gradients upstream). Points with the natural barrier unknown flag (n=112) had a similar shape as the entire distribution, albeit with a higher median steepest gradient (8.59%). Points below artificial barriers (n=42) had a similar median steepest downstream gradient (6.35%) to the distribution of all the points. See Discussion and Recommendations section for discussion on the potential biases associated with each of these barrier categories.

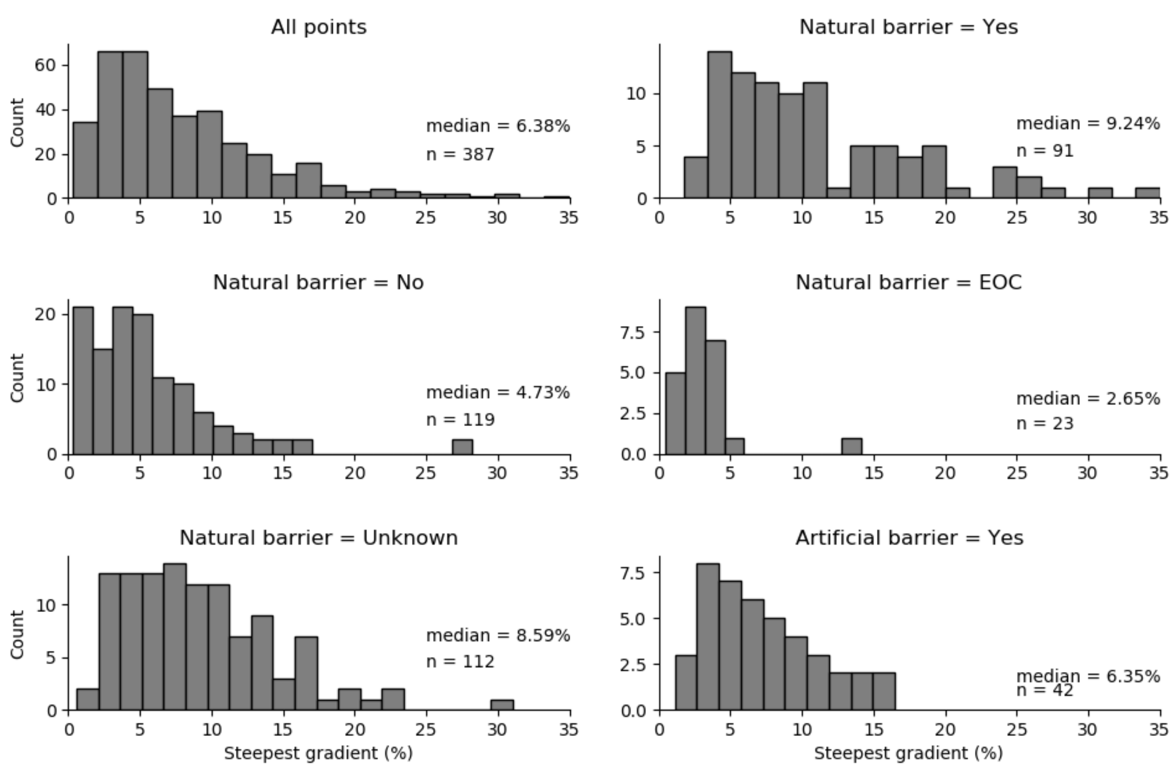

Figure 3. Histograms of the steepest channel gradient downstream of each Coho distribution point. The data are split into natural and artificial barrier categories, and the median and number of observations are printed in each panel. EOC: end of channel.

Figure 4 presents the data as a percent within barrier categories. This illustrates the likelihood of finding fish within each gradient bin by barrier category.

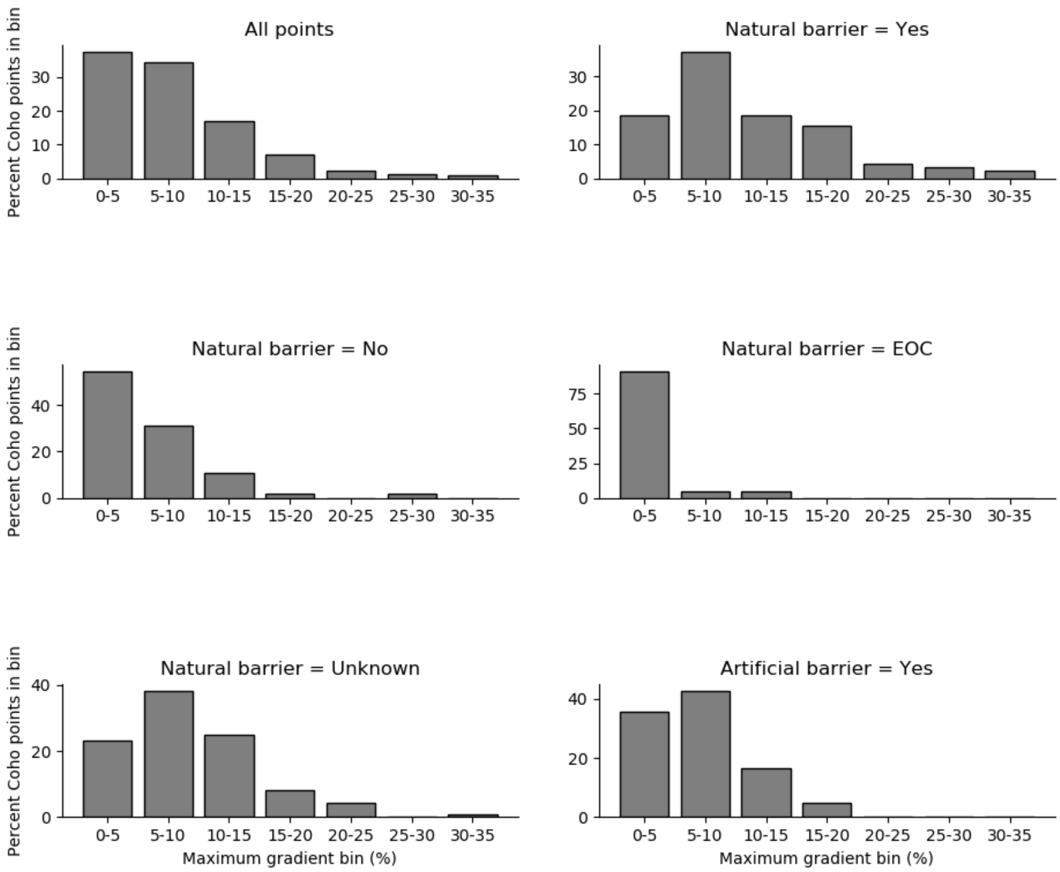

Figure 4. Percentage of Coho points within each gradient bin. The data are split into natural and artificial barrier categories. EOC: end of channel.

Table 2. Maximum downstream gradient results. 5th-95th percentiles are shown in 15% increments.

Category	N.	Min.	Max.	5th	20th	35th	50th*	65th	80th	95th	1st reach**
All points	387	0.32	34.97	1.13	3.37	4.77	6.38	8.88	11.73	18.81	27
Nat. bar. = yes	91	1.71	34.97	3.56	5.05	7	9.24	11.38	16.39	24.96	36
Nat. bar. = no	119	0.32	28.2	0.68	2.22	3.53	4.73	5.95	8.05	14.16	14
Nat. bar. = EOC	23	0.49	14.12	0.72	1.55	2.41	2.65	3.36	4.24	4.97	17
Nat. bar. = unk.	112	0.59	31.03	2.67	4.54	6.26	8.59	10.5	12.97	19.17	36
Art. bar. = yes	42	1.13	16.47	1.92	3.82	4.97	6.35	8.57	10.49	13.5	31

* 50th percentile represents the median.
** Percent of points in each category for which the steepest 30 m reach was the first reach downstream of the Coho distribution point.

Discussion & Recommendations

We think the spatial analysis described here for the Skagit and Samish river basins demonstrates an effective way to quantify the relationship between stream gradients and anadromous fish distributions that can be used to develop an empirically derived anadromous floor recommendation. We based this analysis on the assumption that to understand the relationship between stream gradient and anadromous fish distributions the whole stream network accessible to anadromy (in this case, Coho salmon) needs to be considered. Focusing only on stream conditions at or near the upper extent of anadromous fish use potentially misses stream reaches lower in the watershed that are important to understanding the full range of potential stream gradients anadromous fish are able to navigate. This analysis supports this assumption – the majority of maximum gradient stream reaches navigated by Coho in this study occurred further downstream than at the recorded fish point, regardless of the natural barrier designation (Table 2). For example, slightly more than a third (36%) of the maximum gradients of the fish points associated with known natural barriers were immediately downstream of that point, meaning that almost two-thirds of the maximum gradients associated with those fish were located farther downstream.

In this report we do not offer a recommendation on a permanent anadromous floor gradient. There are two reasons for this, (1) we do not think it is appropriate to base a recommendation for a permanent anadromous floor rule based on a single watershed, and (2) we think a final anadromous floor recommendation needs to be based on policy considerations, informed by technical analysis. Moving forward, we recommend expanding this kind of analysis to additional watersheds to develop an anadromous floor recommendation. We think that for this effort to be successful several decision criteria need to be developed to guide the analysis. These include watershed selection criteria, stream selection criteria, data selection criteria, and ultimately, anadromous floor recommendation criteria. Below we describe those decision criteria and provide initial recommendations on them.

Watershed selection criteria

The Skagit and Samish river basins were good watersheds to try the analyses described here because accurate fish distribution data were available and had been compiled when Coho populations were relatively healthy. Also, high-resolution lidar data had been processed to be hydrologically consistent greatly aiding the python-based GIS analysis (see appendix). Based on our experience, for these methods to reliably work there needs to be (1) high-resolution lidar coverage, (2) an understanding of the stock depletion levels of the anadromous species in that watershed, and (3) high quality (aka confidence in accuracy) anadromous fish distribution data. Evaluating anadromous fish movement patterns in a watershed with depressed stocks and incomplete fish distribution data would be of limited use and reliability.

Species selection criteria

In this analysis, we looked at only one anadromous species, Coho salmon. There are several reasons for this, including the availability of reliable Coho distribution data, the abundance of Coho and the recognition that Coho are ubiquitous across the Salish Sea and often the anadromous species found farthest up the stream network. There are of course other anadromous species, some of which may be of particular significance in other watersheds. To get a more complete understanding of the relationship between stream gradient and anadromous fish distribution, additional species may need to be included in future analyses. For the purpose of defining an 'anadromous floor' based on stream gradient, one approach may be to identify the anadromous species on each stream in the watershed that represents the uppermost extent of anadromous fish use and run the analysis based on those points. This remains a topic for further discussion.

Data selection criteria

We think the most reliable data that can assess the relationship between stream gradient and anadromous distribution are distribution points that represent the upper extent of anadromous fish. Based on this assumption we sorted the fish distribution data by the known conditions present at those points that may affect navigation and use, including the presence of known artificial and natural barriers. We think the strongest anadromous floor recommendation will be based on data points where (1) there is reasonable confidence that the points represent the upper extent of potential anadromous fish access, and (2) upward movement is not blocked by artificial barriers. Additionally, we think it would be useful to understand how anadromy and gradient relate on streams where the full range of gradients of interest[2] (e.g. 5%, 7% and 10%) are known to be present somewhere along the full extent of the stream.

Biases inherent to each barrier category in this data set

To aid in the selection of appropriate fish distribution points, below we present what we consider to be the inherent biases associated with each barrier category in this data set.

Natural barrier = yes

This bin represents the points (n = 91) at (or near) the uppermost extent of anadromous fish access as defined by a waterfall or sustained high gradient reach that is known by experienced fisheries biologists to constitute a limit to anadromy. Therefore, the gradients in this bin are expected to span the full range experienced by Coho in various life history stages. Because the other bins are not associated with the upper extent of Coho use (see below), inclusion of this bin in the anadromous floor discussion may introduce a bias in the results favoring higher gradients when compared to the dataset overall. This bin may be the closest data set that represents the full range of Coho distribution. Because we did not measure the slopes of the upstream barriers themselves, these points do not inform the maximum potential gradients that limit upstream movement of Coho.

Natural barrier = no

These points (n = 119) were placed in streams where Coho were observed, not necessarily in association with a barrier to upward migration. Many of these points are in tributaries near the confluence with mainstem rivers. Because we cannot associate these points with barriers to upward migration, an unknown length of good quality habitat extends upstream from these points, with gradients likely increasing in the upstream direction. Therefore, the inclusion of these points in the anadromous floor discussion may introduce a bias in the results favoring lower gradients.

Natural barrier = end of channel (EOC)

These points (n = 23) primarily represent floodplain environments such as wall-based or groundwater/spring-fed channels. Therefore, the end of anadromous fish passage at these points is constrained by availability of surface water and the termination of channel habitat, not by gradient.

[2] Gradients of interest are those gradients accepted by the Board for consideration in the rule-making, as mentioned in the introduction.

These points are representative of important Coho habitat during certain life history stages. Because most of the 'EOC' points are located on floodplains of rivers and large streams, they almost certainly introduce a bias to lower gradients.

Natural barrier = unknown

Based on our review of lidar digital elevation models, these points (n = 112) appear to be placed in close proximity to natural barriers. However, we were not able to clearly associate these points with known or field-verified natural barriers according to the datasets we consulted and personal knowledge. Therefore, the *natural barrier = unknown* points may be regarded as similar to the *natural barrier = yes* points, albeit with additional uncertainty.

Artificial barrier = yes

These points (n = 42) are located directly below artificial barriers to anadromy such as culverts. Because there may be an unknown upstream length of good quality habitat if these artificial barriers were to be made passable (and gradients tend to increase in the upstream direction), we assume the inclusion of this bin in the anadromous floor discussion will introduce a bias toward lower gradients.

Gradient floor recommendation criteria

The analysis described in this report lends itself to evaluating a range of potential anadromous floor gradients, including the three stream gradients of interest, 5%, 7%, and 10%. The data can be explicitly sorted to determine what percent of the Coho points are associated with streams with maximum gradient reaches that meet or exceed each of these gradient thresholds.

If the methods described here are applied to additional watersheds, we think it would be appropriate to consider, and to the extent possible decide, how the results will be used to make a gradient recommendation before compiling the data and doing the analysis. Fish distribution percentiles may be one way to inform the decision criteria for a gradient recommendation. Table 2 displays fish distribution percentiles from 5% to 95% in 15% increments. The percentile values are the percent of fish distribution points observed above and below the displayed stream gradients. For example, the 50th percentile values (i.e. the median), 50% of the fish distribution points were observed above and below those maximum gradients. These values provide an estimate of the likelihood of anadromous fish accessing and navigating through stream reaches based on a range of gradients.

Study protocols – measurement intervals

This study quantified stream gradients in fixed 30m intervals from the fish point downstream to a distance of 5 kilometers. These distances (30m and 5 kilometers) were somewhat arbitrarily selected due to time constraints, processing time, and additional non-technical factors. We also recognize that using 30 meter fixed length stream segments will tend to round down measured gradients when the stream segments don't closely align with the actual stream profile. Expanding the analyses to other watersheds may necessitate revisiting these distances or utilizing a sliding maximum gradient interval to ensure further bias is not incorporated in the analysis. This may be especially true in watersheds where there are relatively steep stream reaches near the mouth of the river, but which then flatten out above those reaches. The five kilometer distance for many of the fish points measured downstream from the fish points may not capture those reaches and in so doing potentially underestimate the maximum stream gradients anadromous fish successfully navigated to get to those points. An additional analysis may be to look at upstream gradients in concert with some of the barrier status bins used in analysis to understand additional limiting factors associated with Coho distribution in reaches.

Appendix: Details of the GIS method

There are several computational and practical issues that arise when creating programs to extract data from multiple large LIDAR datasets in an automated fashion. First, the Coho distribution data are scattered across the spatial extents of two LIDAR acquisitions (USGS North Puget 2016 and USGS Glacier Peak 2015). Traditionally, extracting data from either LIDAR dataset depending on the location of each point would require mosaicking the two LIDAR datasets together; the memory and computing power requirements of working with the resulting dataset are impractical. To address the need for a single continuous raster dataset from which to extract the slope data for each Coho distribution point, we built a vrt file using the gdalbuildvrt utility of the Geospatial Data Abstraction Library (GDAL). A vrt file is a virtual file that GDAL can use to contain a mosaic of raster datasets without actually mosaicking them. It is very small (on the order of kilobytes), allowing for seamless extraction of data from any of the individual rasters that comprise the vrt without requiring large computational resources.

The second problem inherent to the use of LIDAR is that of loading large datasets into memory to extract the desired slope data. To circumvent this problem, our algorithm first 'clipped' a small window (200 m x 200 m, centered around each Coho distribution point) into the vrt mosaic. We filled the DEM window using the algorithm of Barnes et al. (2014) and created a flow direction grid based on the D8 scheme. The D8 method assumes all flow from each cell follows the path of steepest descent into a single neighboring cell (i.e. flow is not split) and is the most common way to compute flow directions. Next, the algorithm searched down the flow direction pathway starting from the current Coho distribution point, extracted each thalweg pixel, and computed channel gradient between the first and last thalweg pixel of each 30 m reach within the DEM window. In this context, 'thalweg' means the flow direction pathway found by the D8 algorithm. It likely corresponds to the true thalweg in steep and confined settings; in low gradient rivers, the digital thalweg may traverse back and forth across flat areas creating artificially-low slopes. We do not expect this to affect our results because we were only concerned with the highest slope values downstream of each Coho point. When the last 30 m reach within the 200 m x 200 m window was measured, the algorithm repeated the process of clipping a window into the DEM using the last point in the last 30 m reach as the new starting point. After 5 km was measured, the algorithm recorded the maximum gradient of the set of 30 m reaches and continued to the next Coho distribution point. In addition to the maximum gradient, we also recorded X-Y coordinates of the channel thalweg pixels for each 5 km reach used to extract slope at 30 m intervals and the start of the 30 m reach that produced the highest gradient value. The latter two datasets were used to visualize and verify the results of the automated process.

The third problem inherent to LIDAR data is that modeled flows may be obstructed by barriers such as roads, which will have the effect of capturing modeled flow pathways when in reality water is able to flow beneath roads through culverts. The solution to this is to create artificial 'culverts' that, when subtracted from the DEM, have the effect of allowing modeled flows to proceed through each road. We started with a vector dataset of artificial culverts that had already been produced to create a LIDAR-based hydrography layer for the entire Skagit River basin (T. Hyatt, personal communication, 3-20-2019). From this vector dataset we created a raster file with cell values of 1.0 at each artificial culvert location and zeros everywhere else.

At each iteration of the algorithm (i.e. each time a new window was clipped into the DEM), we also clipped a window of the same spatial extent into the artificial culvert raster file. We assigned cell values to the artificial culvert cells that corresponded to a linear gradient between the DEM value at the culvert endpoints, and subtracted the culvert cells from the DEM to form a through-flowing channel pathway. After an initial run of the entire process, we inspected each flow pathway created by the GIS algorithm and identified additional locations where flow had been captured by roads. We added artificial culverts to the inventory at these locations and re-ran the analysis.

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