Evaluation of potential habitat breaks (PHBs) for use in delineating end of fish habitat in forested landscapes in Washington State

Study Design prepared for the Washington Forest Practices Board

(Revised from PHB Science Panel Draft 2019)

~~February 22XXXXXXX~~July 22, 2022

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Preface

In 2018, the PHB Science Panel convened by The Forest Practices Board (FPB) developed a study design to validate potential habitat breaks (PHBs). The study design (PHB Science Panel 2019) was reviewed and approved by Independent Scientific Peer Review (ISPR), however there were varying levels of comments and criticisms from all caucuses participating in the forest practices adaptive management program to particular aspects of the study design and the review process. In 2019, the Forest Practices Board remanded the project to the Department of Natural Resources' adaptive management science program, tasking the Cooperative Monitoring, Evaluation and Research (CMER) committee with revising the study design following CMER's protocols and standards (referenced in Forest Practices Board Manual Section 22). CMER assigned the study design revision to the Instream Science Advisory Group (ISAG). This revised study design was developed by a project team formed within ISAG.

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Summary

The upstream extent of both fish distribution and fish habitat in forested watersheds is influenced by many factors including channel gradient, channel size, channel condition, nutrients, flow, barriers to migration, history of anthropogenic and natural disturbance, and/or fish abundance. The Washington Forest Practices Board has proposed three sets of criteria to be considered in determining potential habitat breaks (PHBs) between fish (Type F) and non-fish bearing waters (Type N) across the state. These criteria are based upon data that can be collected during a single Washington Department of Natural Resources (DNR) protocol electrofishing survey and include channel gradient, bankfull width, and both vertical and non-vertical non-deformable natural ~~barriers~~ obstacles to upstream migration. To evaluate which physical criteria best define the end of fish (EOF) habitat (the uppermost stream segments that are actually or potentially could be inhabited by fish at any time of the year based on habitat accessibility and suitability), detailed information is needed on the uppermost fish location and associated habitat in small streams across Washington State. While some data on habitat conditions at last detected fish locations are available (e.g., from existing water type modification forms [WTMFs] submitted to DNR), these data were found to be insufficient to

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Commented [LP(2]: Green: Really? That's unfortunate. How can they be used to make mods currently if they don't have enough good info regarding fish/habitat?

determine PHBs that defined last detected fish locations and associated habitat.

The purpose of this study is to develop criteria for accurately identifying PHBs and to evaluate the utility of PHB criteria selected by the Board for use in the Fish Habitat Assessment methodology (FHAM) as part of a water typing rule. The study is designed to assess combinations of gradient, channel width, barriers to migration, and other physical habitat and geomorphic conditions associated with uppermost detected fish locations. This will 1) inform which Board identified PHB criteria most accurately identify the upstream extent of fish habitat in an objective and repeatable manner as applied in the FHAM and 2) evaluate whether an alternative set or combination of empirically derived criteria more accurately achieves this goal. Additionally, this study is intended to provide insight into how last detected fish points and associated stream characteristics may vary across geography, seasons, and years.

The study will be conducted across two sampling seasons (spring and fall/winter) in each of three years at 350 sites statewide; 160 in Eastern and 190 in Western Washington. Upstream last detected fish locations will be determined during each season at each site following modified DNR protocols for electrofishing surveys. Once the uppermost fish is located during each sampling event, the last detected fish location will be flagged, GPS coordinates will be recorded, and a longitudinal profile habitat survey will be conducted to characterize habitat and geomorphic conditions 660 ft (200 meters) downstream and 660 ft upstream of the last detected fish location. To evaluate seasonal changes in the location of the last detected fish, the sites that can be accessed in the fall/winter high-flow season will be sampled on a rotating panel basis. One quarter of the sites will constitute the fixed portion of the panel and will be surveyed every fall/winter, and the remainder will constitute the rotating portion. One third of the rotating portion will be sampled each year in addition to the fixed portion such that every accessible site will be sampled at least once during the fall/winter. If a last detected fish location changes during any subsequent survey, additional longitudinal profile survey data will be collected to ensure that there are channel data 660 ft above and 660 ft below last detected fish locations for all seasons and years. Data will be analyzed to determine the combinations of gradient, channel width, and other geomorphic features associated with the furthest upstream last detected fish locations across all seasons and years at each site, which will define PHBs and EOF habitat, and whether these vary across Eastern and Western Washington. The results of this study will be used to evaluate the effectiveness of PHB criteria in determining the regulatory break between fish (Type F) and non-fish bearing (Type N) waters.

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Commented [JK3]: YELLOW: What is the level of uncertainty (as determined through the evaluation of "effectiveness") associated with using PHBs to correctly identify EOF?

This is the science question:
How accurately can EOF be predicted based on a set of PHB criteria?
That answers the policy question regarding "risk."
How often is it wrong and by how much?

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Table of Contents

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List of Acronyms

AMP	Adaptive Management Program
BFW	Bankfull Width
CMER	Cooperative Monitoring, Evaluation & Research Committee
DNR	Washington State Department of Natural Resources
DPC	Default Physical Characteristics
eDNA	Environmental DNA
EOF	End of Fish (Last detected fish following a Protocol Survey)
EOFH	End of Fish Habitat
F/N Break	Regulatory break between fish and non-fish bearing waters
FHAM	Fish Habitat Assessment Method
GIS	Geographic Information System
HCP	Habitat Conservation Plan
ISPR	Independent Scientific Peer Review
NVO	Non-vertical obstacle
PHB	Potential Habitat Break(s)
TFW	Timber, Fish & Wildlife
Type F	Fish Bearing Streams
Type N	Non-Fish Bearing Streams
WTM	Water Type Modification

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WTMF	Water Type Modification Form

Introduction

In Washington State, forest practices are regulated by the Forest Practices Act (RCW 76.09) established by the legislature, with rules established by the Washington Forest Practices Board (Board). The goals of the rules include protecting public resources (water quality, fish, and wildlife) and maintaining an economically viable timber industry. Rules pertaining to aquatic and riparian habitats are specifically included in the Forest Practices Habitat Conservation Plan (HCP), which provides coverage for approximately 9.3 million acres of forestland in Washington (6.1 million acres west of the Cascade Crest and 3.2 million acres in eastern Washington). Specific timber harvest and road prescriptions (rules) are applied to waters containing fish to protect fish and their habitats.

The Board is responsible for rulemaking and overseeing the implementation of forest practice rules. The evaluation of the effectiveness of these rules is ~~directed~~ administered by the Adaptive Management Program of the Washington Department of Natural Resources (DNR). Water typing is an important part of applying contemporary forest practice rules since prescriptions in riparian areas are based in part on whether streams are or potentially could be used by fish. Streams identified as having fish habitat are classified as Type F waters, defined in the water typing rule (WAC 222-16-030), and have specific riparian buffer prescriptions and fish passage requirements. Fish habitat is defined in WAC 222-16-010 as "…habitat, which is used by fish at any life stage at any time of the year including potential habitat likely to be used by fish, which could be recovered by restoration or management and includes off-channel habitat." Currently, an interim rule allows for the delineation of Type F waters through the use of either default physical ~~criteria~~ characteristics (WAC 222-16-031) or a protocol electrofishing survey. DNR provides a map showing stream segments of modeled fish habitat. The Forest Practice Rules require forest landowners to verify, in the field, the type of any regulated waters ~~as~~ identified within proposed harvest areas prior to submitting a forest practices application/notification. Landowners may use the default physical criteria or the results from protocol survey electrofishing to identify the regulatory F/N break. Landowners are encouraged to submit a Water Type Modification Form (WTMF) to the DNR to make permanent changes to the water

Commented [LP(5]: Green: suggest clarifying- rules regarding timber harvest

Commented [LP(6]: Green: Administered?

Commented [LP(7]: Yellow: I don't see what these criteria are anywhere. Should be listed

Commented [LP(8]: Green: suggest adding a blurb about why rules differ between Type F and N type maps. Thousands of WTMFs have been submitted to DNR to modify water types and modify the location of the break between Type F and Type N waters.

The Board is currently in the process of establishing a permanent water typing rule. Ultimately, the rule must be implementable, repeatable, and enforceable by practitioners and regulators involved in the water typing system. An important part of the permanent rule will be guidance on a specific protocol to determine the regulatory break between Type F and Type N waters. The Board is considering the use of a fish habitat assessment method (FHAM) that incorporates known fish use with potential habitat breaks (PHBs) to identify the upstream extent of fish habitat. The Board recommended that PHBs be based on permanent physical channel characteristics such as gradient, stream size, and/or the presence of ~~natural~~ non-deformable vertical and non-vertical natural obstacles as potential barriers to upstream fish movement (WA Forest Practices Board 2017).

Study Purpose

The purpose of this study is to develop criteria for accurately identifying PHBs~~PHBs~~ and to evaluate the utility of PHB criteria selected by the Board for use in the Fish Habitat Assessment methodology (FHAM) as part of a water typing rule. The study is designed to assess which combinations of gradient, channel width, barriers to migration, and other physical habitat and geomorphic conditions are associated with uppermost detected fish locations. This will 1) inform which Board-identified PHB criteria most accurately identify the upstream extent of fish habitat in an objective and repeatable manner as applied in the FHAM and 2) evaluate whether an alternative set or combination of empirically derived criteria more accurately achieves this goal (CMER 2020). Additionally, this study is intended to provide insight into how last detected fish points, upstream extent of fish~~EOF~~ habitat based on FHAM, and PHBs proposed by the Washington Forest Practice Board may vary across geography, seasons, and years. The Board is expected to use the study findings to inform which PHB criteria to use in FHAM.

It is important to note that this study is not intended to evaluate the current water typing system or the FHAM; nor~~or~~ is it intended to describe how the regulatory Type F/N break should

Commented [LP(9]: Yellow: Should touch more on the background, i.e. the WAC directs DNR to lead development of a GIS-based water typing model. The WAC is pretty specific about what is supposed to happen, so it should be included.

Also, should describe the current physical habitat criteria being used to make breaks. Somebody at some point thought that the interim system had tolerable accuracy regarding channel width, gradient, basin size. What made them think those were acceptable interim criteria? Please explain.

Commented [LP(10]: Green: Who verifies their accuracy?

Commented [LP(11]: Greenish yellow: Partially based on guidance in the WAC. And what other information/knowledge? should describe

Commented [LP(12]: Overall, this study design is commendable. There's a lot of good technical elements. But I think it's not quite done yet.

I'm worried about this PHB study and broader water typing effort having an unclear vision and goals, and ending up with unusable data as discussed on page i, or a system that folks apparently think doesn't work well like the current interim system, or something that is not accurate enough to replace the current system. I think we need to reconsider how we got to this point and have a more clear vision and plan for how to fix whatever is broken. Otherwise we are tinkering in a piecemeal fashion and may overlook some of the critical structural and functional elements/processes that are needed to develop a functional, reliable system. Not sure how to say it better than this.

Commented [MM13]: Green. A definition of PHB would be most welcomed at a location of your convenience.

Commented [MM14]: Yellow: Will these results for PHBs be used to revise DPC to be used in the FHAM?

Commented [LP(15]: Green: The WAC says we need 95% accuracy

Commented [MM16]: yellow: Is this the EOF habitat from a FHAM or EOF as determined by the last fish?

Commented [JK17]: YELLOW: With Decision Criteria in mind... Is the goal of this study to be descriptive (informative) or actionable (establish one or more decision points)?

Commented [MM18]: yellow. How does this study fits into the AMP's goal of improving the management of streams. How will these results inform the management of Washington streams? Will the Board manual or WAC nee...

Commented [MM19]: Yellow. Are you not addressing this with questions 5 and 10?

be determined. PHBs are defined in FHAM as permanent, distinct, and measurable changes to in-channel physical characteristics. Other factors such as temperature, flow, water quality, population dynamics, anthropogenic and natural disturbance, and biological interactions are important covariates that might influence the distribution of fishes but do not affect PHBs. Therefore, they are not being evaluated in this study.

Project Research Questions

The following project-specific research questions were developed to address key uncertainties and information needed to evaluate the performance of the PHB criteria provided by the Washington Forest Practices Board and empirically derived alternatives. They also address certain aspects of the CMER Workplan Rule Group critical questions listed in Appendix A.

UPSTREAM-MOST FISH LOCATIONS

1. **How do the locations of the last detected fish vary interannually?**
2. **How do the locations of the last detected fish vary seasonally?**
3. **How do the locations of last detected fish vary geographically across the state of Washington?**

HABITAT ASSOCIATED WITH UPSTREAM-MOST FISH LOCATIONS

4. **How do the physical channel and basin characteristics (e.g., bankfull width; average gradient, basin size) associated with the identified end of fish habitat vary geographically across the state of Washington?**
5. **Where the location of the last detected fish changes (seasonally or interannually), how does that influence which~~the~~ PHB ~~that is~~would be associated with the F/N break and how frequently does that occur?**
6. **How d~~D~~o the physical channel features at the locations initially identified as PHBs change ~~in~~ over the course of the study~~time~~?**
7. **How often ~~D~~do~~Do~~ similar features appear to limit upstream fish distributions in some contexts but not others (e.g., further into the headwaters vs. downstream; different flow levels)?**

PHB PERFORMANCE ANALYSES

Commented [LP(20]: Yellow: This is somewhat confusing. We are going to assess physical attributes that are associated with fish presence and that are part of the current system, but we aren't evaluating the current system? Still not getting the problem with the current system. How could we know that the current interim system of physical criteria isn't the best alternative or good enough if we don't evaluate it?

In the first sentence above it is stated that one purpose is to "evaluate the utility of PHB criteria selected by the Board". These parameters are more or less the same than what is in the current system. I'm not seeing a clear demarcation line between the stated purpose and the statement of scope. ...

Commented [MM21]: Red. I'm not sure about this one. The degree in which a PHB is influenced by all these covariates varies in time and place. In addition, there is th ...

Commented [MM22]: Green: Anthropogenic and natural disturbances as well

Commented [JK23]: These are all very descriptive and exploratory – there are no hypotheses officially presented ...

Commented [JK24]: YELLOW: these are descriptive question that, when answered, can help define a "problem" or a hypothesis. ...

Commented [MM25]: Green. Yes, such as eastside from westside

Commented [MM26]: Yellow: at the PHB? Basin characteristics such as GIS-derived?

Commented [MM27]: Yellow: or at the PHB since EOF habitat isn't PHB, yes?

Commented [MM28]: Yellow: …with repeated measures either seasonally or interannually,

Commented [JK29]: RED: This is worded in a manner that the PHB is subject to influence, suggesting that the ...

Commented [JW30R29]: Could change language to read, "how does that influence WHICH PHB would be associated…"

Commented [MM31]: Yellow: Well it is a stream….LOL…and you have measurement error (you'll need to define what constitutes a meaningful difference).

Commented [JK32]: GREEN: good question. In the Intro there is a notion of "permanence" in nature. Some features are likely to remain long after us, however it really only ...

Commented [MM33]: Yellow Yes! An important component to this is, how does the upstream and downstream barriers compare within a stream?

Commented [JK34]: YELLOW: Here are potentially actionable questions. Ultimately it is a policy type choice based on social tolerance of certainty. So given these ...

8. **Which combinations of physical channel features and basin characteristics (for example, gradient, channel width, barriers to migration) best identify the end of fish habitat relative to the location of the last detected fish?**
9. **Can protocols used to describe PHBs be consistently applied among survey crews and be expected to provide similar results in practice?**
10. **How well do the PHB criteria provided by the Washington Forest Practices Board accurately identify the EOF habitat when applied in the Fish Habitat Assessment Methodology (FHAM)?**

We will use data from electrofishing and physical habitat channel surveys in a spatially balanced sample of 350 streams across Eastern and Western Washington to address these study questions and evaluate proposed criteria to be used as potential habitat breaks in the FHAM.

Background

Over the past 20 years, protocol electrofishing surveys have been conducted under WAC 222-16-031 with guidance provided by Board Manual Section 13 to determine the upper extent of Type F waters. These surveys often incorporate additional stream length upstream of the uppermost detected fish to include habitat "likely to be used by fish" (defined in WAC 222-16-010). Throughout Washington, the uppermost fish[1] detected during protocol electrofishing surveys is most often a salmonid, and in around 90% of cases the uppermost fish is a cutthroat trout (*Oncorhynchus clarki*) (D. Collins, Washington Department of Natural Resources, unpublished data; Fransen et al. 2006). Other salmonid species that have been documented at uppermost fish locations on water type modification forms across Washington include rainbow trout (*O. mykiss*), brook trout (*Salvelinus fontinalis*, an introduced non-native that has become established in many Washington streams), and (rarely) bull trout (*S. confluentus*). In headwater reaches that are accessible to anadromous fishes, coho salmon (*O. kisutch*) juveniles have been reported on occasion as the uppermost fish. Of the non-salmonid species documented at uppermost fish sites on WTMFs in western Washington, sculpins (*Cottus* spp.) were most prevalent, followed by brook lamprey (*Lampetra* spp.), and less commonly dace

[1] WAC 222-16-010: "Fish" means for purposes of these rules, species of the vertebrate taxonomic groups of Cephalospidomorphi [lampreys] and Osteichthyes [bony fish].

Commented [MM35]: Yellow: basin area at PHB?

Commented [MM36]: Yellow: I suggest you are assessing the multivariate response of the three PHB types – each with well-defined variables to characterize them (suggested in a separate comment).

Commented [JB37R36]:

Commented [LP(38]: Red: Most accurate may not be accurate enough. Should have decision criteria for what will be deemed accurate or not.

Commented [JW39R38]: Agree we need to include information on quantitative performance criteria… based on probability of fish use and/or potential fish use. Will be addressed though additional detail in analysis section.

Commented [JB40R38]: Least frequently overcome by fish? Probability that feature would be passed.

Commented [LP(41]: Yellow: important QA/QC element. Not clear from the document how consistency will be evaluated. I only saw description of formal training and repeated measures by different crews. But not how consistency will be assessed. Should be decision criteria for this too. For example, a protocol will be determined to be consistently applied if repeated measurements by separate crews differ by less than 10%, on average.

Commented [LP(42]: Yellow: Need to translate into decision criteria to define "how well" and "accurately"

WAC 222-16-030 sets an accuracy objective of 95%.

Commented [MM43]: Yellow: I suggest that explicitly stating the relevant WAC language when applicable such as the legal definition of a fish from WAC 222-16-010: "Fish" means for purposes of these rules, species of the vertebrate taxonomic groups of Cephalospidomorphi (lampreys) and Osteichthyes (bony fish). I think you can explicitly state that all fish species must be considered, but the PHB criteria from this report will be primary derived from cutthroat trout, which are known to be the upper most species. I suggest you limit the analysis to either just cutthroat or separate out cutthroat from all other species. If the last fish species is not cutthroat, then factors other than PHB are likely responsible. The issue is related to resident species that don't have to migrate from the main channel every year.

The exception to this is non-anadromous lamprey species. It will be interesting to see where you find them but eDNA might be a better way to sample them. This may be a topic for a future study.

(*Rhinichthys* spp.).~~,~~ three-spine stickleback (*Gasterosteus aculeatus*),~~,~~ and Olympic mudminnow (*Novumbra hubbsi*).~~.~~ The only uppermost non- salmonid fish species recorded in east-side Washington streams were sculpins.

Many factors can limit the distribution of fishes including barriers to migration, stream gradient, ~~and~~ flow, and ~~/~~channel size. ~~.~~ Understanding the current science on how these factors influence fish distribution is important when discussing how they can be used to most accurately define the upstream limits of fish habitat in forested streams of Washington State.

Commented [JK44]: GREEN: Are flow and channel size considered together?

Makes sense, I wonder if there is a way to better articulate that and remove the / so that it is more clear.

Obstacles~~Barriers~~ to Migration

Natural stream habitat breaks that might obstruct or completely block upstream fish movement to apparently suitable habitat include: vertical drops, ~~steep~~ cascades, bedrock sheets, and trenches ~~/~~ or ~~trench/~~chutes (Hawkins et al. 1993; Figure 1).

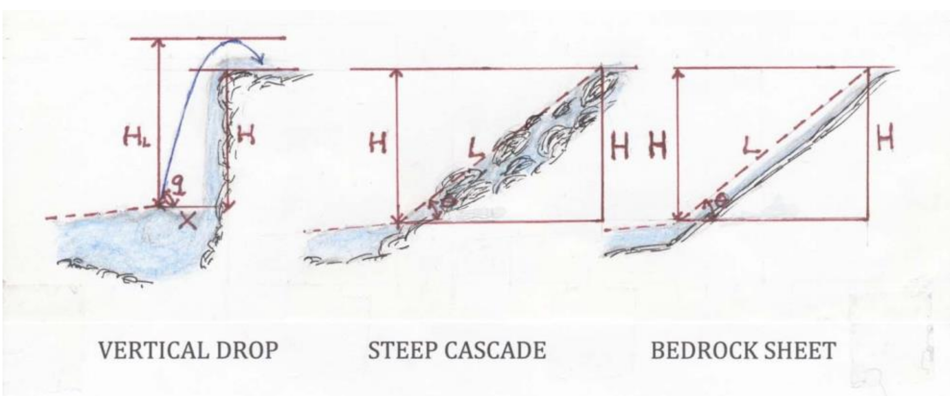

Figure 1. Three types of ~~habitats~~ features that could pose obstacles or barriers to upstream movement of headwater fishes. (PHB Science Panel 2019)

Commented [MM45]: Green. How does a steep cascade differ from a cascade? LOL!

In my view, the three categories are Permanent Natural Barrier (falls and chutes), stream gradient (or channel slope barrier), and minimum stream size.

Commented [MM46]: Yellow. Note that the height of the fall is not measured correctly – the top of the falls should be measured at bed elevation. I realize this is not the place to present the details of how you measure the stream characteristics. I would suggest that the methods must be through a "fish-eye" perspective (which differ from standard unit measuring protocol) **to reduce the variability around potential barriers of given characteristics is passable.** For example, not all waterfalls of a given maximum height present the same resistance to migration at a given flow. For example, the falls might be passable in a side channel that skirts the falls – the measured vertical height is the minimum distance the fish must traverse to pass.

The ability of fishes to pass such obstacles is associated with the interactions between their swimming and leaping abilities, environmental factors such as flow and temperature and the dimensions of the obstacles. The swimming ability of fishes is typically described in terms of cruising, prolonged, and burst speeds, which are measured in units of body lengths per second

(Watts 1974; Beamish 1978; Webb 1984; Bell 1991; Hammer 1995). Body form also affects swimming ability, with more fusiform body shapes being advantageous for stronger burst speeds in fishes such as cutthroat and rainbow trout (Bisson et al. 1988; Hawkins and Quinn 1996) in comparison to some other fishes, such as sculpin (*Cottus* spp.), commonly found at EOF locations. Cruising speed is the speed a fish can sustain essentially indefinitely without fatigue or stress, usually 2–4 body lengths per second. Cruising speed is used during normal migration or movements through gentle currents or low gradient reaches. Prolonged speed (also called sustained speed) is the speed a fish can maintain for a period of several minutes to less than an hour before fatiguing, typically 4–7 body lengths per second. Prolonged swimming speed is used when a fish is confronted with more robust currents or moderate gradients. Burst speed is the speed a fish can maintain for only a few seconds without fatigue, typically 8–12 body lengths per second. Fish typically accelerate to burst speed when necessary to ascend short, swift, steep sections of streams; to leap obstacles; and/or to avoid predators.

When leaping obstacles, fish come out of the water at burst velocity and move in a parabolic trajectory (Powers and Orsborn 1985). Relationships for the height attained in the leap, and the horizontal distance traversed to the point of maximum height are often used to assess barriers. Depth at the point of takeoff is important for enabling fish to reach burst velocity. Stuart (1962) found water depth of at least 1.25 times the height of an obstacle to be required for successful upstream barrier passage. More recently, however, Kondratieff and Myrick (2006) reported that small brook trout (size range 100-150 mm) could jump vertical waterfalls as high as 4.7 times their body length from plunge pools only 0.78 times the obstacle height, and larger brook trout (size ranges 150-200 mm and 200 mm+) could jump waterfalls with heights 3 to 4 times their body length if the plunge pool depth was at least 0.54 times the obstacle height.

To successfully ascend 4.7 body lengths in height, a back-calculation from the Powers and Orsborn (1985) trajectory equation yields a burst speed of 22 body lengths per second (11.7 feet per second) for the 100-150 mm body-length brook trout reported by Kondratieff and Myrick (2006). If it is assumed that other salmonids (e.g., cutthroat, rainbow trout or coho salmon) could perform as well as brook trout in the size range typically found at uppermost fish locations in Washington (Sedell et al. 1982; Fransen et al. 1998; Liquori 2000; Latterell et al. 2003; Peterson et al. 2013), then a burst speed of 22 body lengths per second (11.7 feet per second) would allow the largest fishes in the size range typical of headwater-dwelling salmonids (6.3 in, 160 mm) to leap a vertical obstacle 2.6 feet high, whereas a vertical obstacle of 3 feet high would be impassable.

When leaping is not required, fishes may ascend steep cascades and other high-velocity habitat units (Hawkins et al. 1993) by seeking pockets of slow water interspersed in areas with turbulent flow (e.g., boundary layers near rocks or logs). For example, Bisson et al. (1988) reported the average water velocity was only 24.8 ± 3.2 cm/s (0.8 ft/s) in shallow (10.0 ± 1.4 cm; 4 inches) cascade habitat units of small western Washington streams. It is possible that fish may ascend streams during periods of elevated flow by moving along the channel margins where water velocities are reduced relative to mid-stream and small falls and boulder cascades are partially or completely submerged.

Although studies examining fish migration through potential non-vertical obstacles are rare, some studies have examined brook trout movement through steep cascades and reported fish ascending cascades of more than 20% gradient (Moore et al. 1985; Adams et al. 2000; Björkelid 2005). For example, Adams et al. (2000) reported that adult brook trout ascended cascades with slopes of 13% that extended for more than 67 m, and 22% for more than 14 m as well as adult brook trout ascending a waterfall 1.2m high. Similarly, Björkelid (2005) reported invasive brook trout colonizing 18 headwater streams in Sweden and found they ascended stream segments with slopes of 22% (measured with a clinometer) and 31% (measured with GIS).

Gradient

Commented [LP(47]: Green: good section
Commented [JB48R47]: Thank you.

In Washington streams, fish (not necessarily the uppermost fish) have been observed in headwater segments with overall slopes as steep as 31% (S. Conroy, formerly Washington Trout [now Wild Fish Conservancy], unpublished data), 35% (J. Silver, Hoh Indian Tribe, unpublished data; D. Collins, Washington Department of Natural Resources, unpublished data), and in reach gradients of 25% and steeper in Oregon streams (C. Andrus, Oregon Department of Forestry, unpublished data; Connolly and Hall 1999). This range of channel steepness is consistent with other observations in western North America (e.g., Leathe 1985; Fausch 1989; Ziller 1992; Kruse et al. 1997; Watson and Hillman 1997; Dunham et al. 1999; Hastings et al. 2005; Bryant et al. 2004, 2007) and Europe (Huet 1959). In the "trout zones" of European rivers (headwaters), brown trout (*Salmo trutta*) predominate and reach gradients may be 10 to 25% or steeper (Huet 1959; Watson 1993). In Washington, it is important to note that fish presence in streams steeper than 15% accounted for only 10% of reported occurrences in forested streams (Cole et al. 2006; J. T. Light, Plum Creek Timber, unpublished data). Kondolf et al. (1991) reported that often the water surface slopes where fish occur in step-pool habitats have much lower local gradients than the overall reach gradient and may range from only 0.4 to 4%, even where overall reach gradients may be as high as 35% (Figure 2). These observations indicate that in some cases fish habitat in headwater streams can extend into the types of steep step-pool and cascade reaches described by Montgomery and Buffington (1993).

Commented [MM49]: green. Nice figure. This seems like a good place to mention that from a fish-eye view, "A" is easer to navigate than "B", because of the resting places in the first are lacking in the second (referring to the swimming ability argument above). Therefore, the two reaches - although of the same length and gradient - will differ in passing fish – a source of the variability in determining PHB.

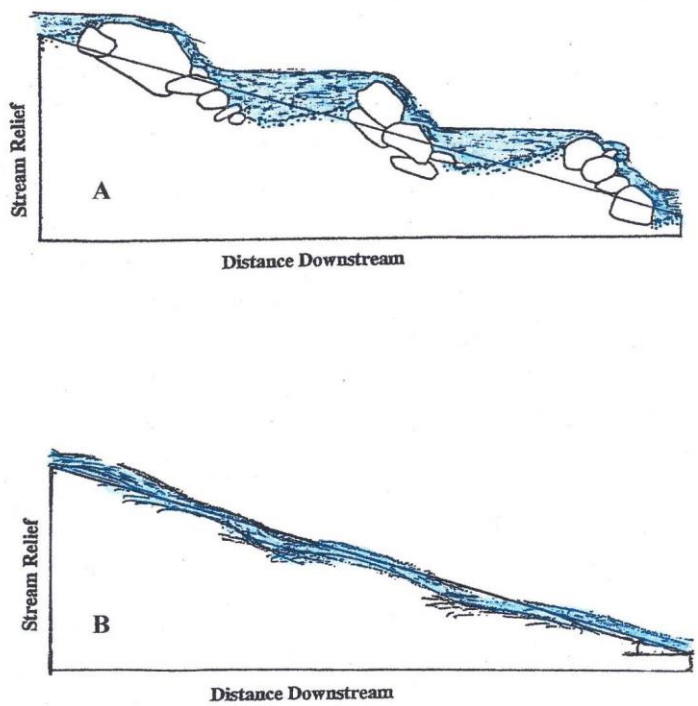

Figure 2. Two very different profiles of a headwater reach with the same overall reach gradient. Illustration (A) demonstrates how roughening elements create local gradients that are lower than the overall reach gradient, while reaches without such features (B) do not. (PHB Science Panel 2019)

Flow and Channel Size

Bankfull width (BFW) has been found to reflect the stage of discharge at which a stream does its habitat-building work (Andrews 1980; Leopold 1994; Rosgen 1996). Studies have shown that BFW is correlated with drainage area and varies with climate, geology, and topography of the basin (Castro and Jackson 2001). For example, Beechie and Imaki (2014) developed an equation for BFW for Columbia Basin streams based on annual precipitation and catchment (drainage) area. Although that equation was developed for larger streams, the PHB Science Panel (2019)

Commented [MM50]: Yellow. I wanted to make a suggestion on methods. An easy way to accommodate the variable roughness (step pool or cascade) is to measure the minimum grades over a given distance. So, for “A”, the **minima** at 4 locations would be much less than the overall gradient, which is what is measured in the field. The steps in A are the potential barriers not the overall gradient. In “B”, you just need the overall gradient for a given minimum distance. The PHB variables for stream gradient PHB that could be explored are length of the unit at a given slope after accounting for substrate (e.g., bedrock vs boulder).

Commented [LP(51]: Yellow: Bankfull width seems like highly unreliable indicator of fish presence. I’ve seen fishless streams of 20ft+ bfk width, and 1ft bkf width streams with fish. Even found fish in a small pool in a nearly ephemeral stream where there was no other water for hundreds of yards up or downstream. There’s not enough science here to justify using it as an indicator.

Is there any literature addressing variability in flow as a fish barrier? For example, have there been any observations of high flow events temporarily flushing fish out of a stream reach or seasonal, localized stream intermittency affecting distributions, e.g. localized channel aggradation that results in a gap in surface flow connectivity during summer?

To my surprise in Oregon I once found fish upstream of a section of a very small channel (<2ft bkf width) that several times in a row flowed a subsurface (like 2-3ft below the surface) for several meters beneath duff and soil and buried logs. Depending on the observer, if one were walking upstream and reached the subsurface section, they might assume that was the end of fish and stopped looking. Although a rare occurrence, I recommend that the protocols be able to address odd situations like this in a consistent manner.

tested it using empirical BFW data from multiple smaller streams across Washington State and found that it accurately predicted BFW in headwater streams. However, Castro and Jackson (2001) found that while BFW and drainage area relationships worked well in areas of similar lithology/geology and precipitation regimes to those for which they were developed, they were less useful in the pacific coastal areas of western Washington where the geology and precipitation patterns are highly variable. Researchers continue to work on developing accurate and usable relationship models for highly variable headwater streams, which may become useful as more precise information and mapping of lithology, topography, and precipitation becomes available.

Because of the perceived relationship between channel width and discharge, BFW is often used as a surrogate for stream discharge (area, depth, and velocity), which is often important for determining the uppermost fish and extent of fish habitat (Harvey 1993). Fransen et al. (1998) estimated mean annual flow rates at the upstream extent of fish distribution for 79 streams in the western Cascade foothills and Willapa Hills in Washington and found that 90% of these streams had mean annual flows of ~3.5 cfs or less at the upper boundary of fish presence; 80% had mean annual flows of ~2 cfs or less at the upper boundary; 65% had mean annual flows of ~1 cfs or less at the upper boundary; and approximately 25% of the sites had mean annual flows of 0.5 cfs or less at the upper boundary (Figure 3).

Commented [MM52]: Green. Will mean Q be one of the basin characteristics used in the analysis?

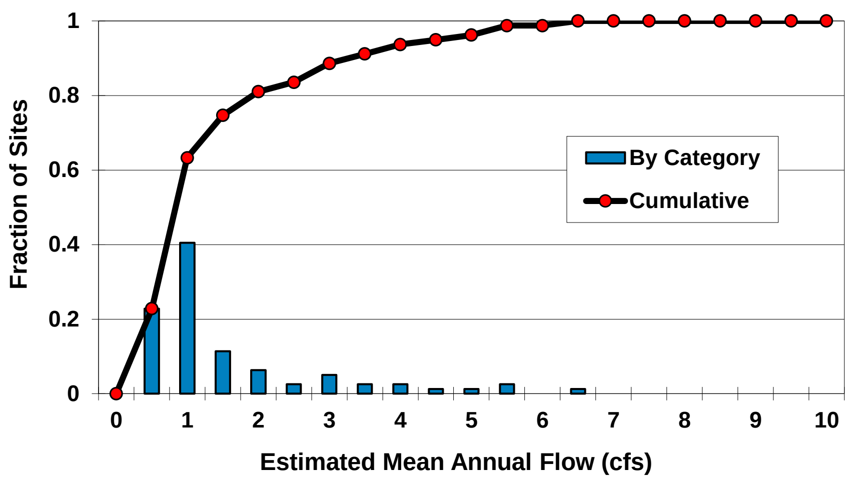

Figure 3. Estimated mean annual flows at uppermost fish locations in 79 streams in western Washington (Cascade foothills and Willapa Hills; Fransen et al. 1998).

Food Availability

Commented [MM53]: Green. Food availability is a secondary effect on PHB. That is, the persistence of a resident population after seeding a reach may be a limiting factor but it certainly isn't directly related to impeding upstream movement. It also may limit the population size resulting in low capture efficiencies from electrofishing. You could delete.

Many studies, particularly in Pacific Northwest streams, have demonstrated strong food limitations for fish inhabiting (using) small streams (Warren et al. 1964; Mason 1976; Naiman and Sedell 1980; Bisson and Bilby 1998). Headwater segments are often characterized by closed forest canopies, requiring primary energy sources from allochthonous inputs of coarse particulate organic matter (CPOM). Shredder organisms occur in these reaches and feed on this CPOM. These aquatic organisms, along with any terrestrial invertebrates that fall into the stream, comprise the food base for trout and other predators (Vannote et al. 1980; Hawkins and Sedell 1981; Triska et al. 1982; Wipfli 1997). The total production of macroinvertebrate organisms is substantially lower in small headwater stream reaches than in the larger, lower-gradient reaches further downstream (Northcote and Hartmann 1988; Haggerty et al. 2004). As a result, resident fishes in small headwater stream reaches tend to be small bodied, which limits their ability to negotiate obstacles to upstream movement and migration.

Fish Habitat Assessment Method (FHAM)

Water typing surveyors have used professional judgment to estimate "habitat likely to be used by fish" when proposing regulatory fish bearing/non-fish bearing (F/N) water type ~~(F/N)~~ breaks. Stream segments that are accessible to fish and exhibit the same characteristics to those of fish-bearing reaches are typically assumed to be fish habitat, whether or not fish are present at the time of a survey. Surveyors have assessed barriers and measurable changes in stream size and/or gradient to estimate the EOF habitat (Cupp 2002; Cole et al. 2006). Although research is somewhat limited, the upstream extent of fish distribution in forest lands appears to be strongly influenced by stream size, channel gradient, and access to suitable habitat (Fransen et al. 2006; PHB Science Panel 2018a). In response to these findings, the Board embraced the concept of a Fish Habitat Assessment Methodology (FHAM) developed by a diverse group of AMP technical stakeholders intended to be repeatable, implementable, and enforceable (WA Forest Practices Board 2018; WA DNR, 2019). The FHAM will utilize PHBs that reflect a measurable change in the physical stream characteristics at or upstream from a detected fish point, above which a protocol electrofishing survey would be undertaken (Figure 4). The first PHB located at or upstream from the last detected fish would serve as the end of fish habitat (F/N Break) when no fish are detected above this PHB.

Commented [MM54]: Green. And there is no way around that – statistical models provide a good estimate, but they can't replace surveys. You need to make defensible calls based on legally defined DPC, which I assume is a goal of this study.

Commented [MM55]: Red. I suggest that there are three issues that need to be addressed in this proposal inserted in places in the document as you see fit. First, the reason that there may not be fish there is in part, that the fish distribution expands and contracts seasonally and annually, which is driven in part by size and duration of storm flow. The legal definition of Type F is the maximum expanded distribution. Second, there may be transient barriers that block upstream fish passage. Third, electrofishing in headwater streams can have a low capture efficiency because of typically low abundances and the reaches can be very difficult to shock effectively. In short, electrofishing answers the wrong question – "is there a fish there today"- versus "could there be a fish here". This study can inform all three of these issues.

Commented [JW56R55]: We can address most of this with current sampling scheme (season/annual, etc.). Transient barriers aren't PHBs… do we need to specify this or does that language exist? RE capture probability that is also partially addressed through repeated sampling. We cannot definitively say whether changes in location of uppermost fish are due to fish movement or previous false negative… both can result in "variability". Large sample size will also help to address this concern.

Commented [MM57]: Green. An FYI. In most cases, especially in steep headwater streams (e.g., gradient), electrofishing is not necessary as potential fish habitat become even more unlikely as you move upstream (lower stream profile to the left. The judgement comes with the top stream profile where it could be at either arrow, but certainty increases with the upstream arrow if the stream bench is habitat.

If the electrofishing is optional, then the FHAM can be done any time of the year.

Commented [MM58]: Green. Are these PHB from table 1?

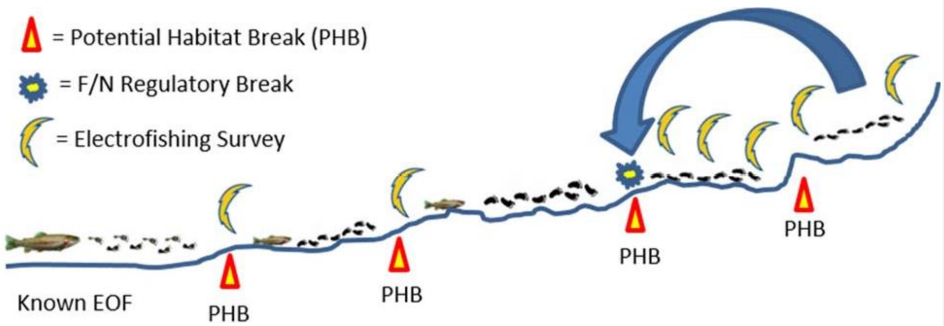

Figure 4. Example of how the PHB criteria and Fish Habitat Assessment Methodology (FHAM) will be applied in the field. The first step is to identify the last detected fish (end of fish) location. Once the point is identified, the survey team would begin to measure bankfull width, gradient, and barrier (obstacle) criteria while moving upstream. Once a point in the stream meeting one of the PHB criterion (gradient, barrier, change in channel width) is identified, the survey team would apply a fish survey (e.g., electrofishing) upstream of the PHB to determine if fish are present upstream. If sampling yields no fish ¼ mile upstream, then the F/N break would occur at the location where the survey commenced (see arrow in the figure). If fish are encountered above any PHB, the process of measuring and moving upstream would repeat until fish are not encountered. (PHB Science Panel 2019)

Per FHAM, PHBs are based on stream size, gradient, and access to fish habitat. The PHB Science Panel reviewed the available science and data on PHBs and provided recommendations to the Board for specific PHB criteria for eastern and western Washington (PHB Science Panel 2018a). The Panel considered a variety of potential PHB attributes, including the physical features of a stream channel, water quality and quantity parameters, and other factors that might contribute to measurable habitat breaks. These attributes were evaluated for the ability to simply, objectively, accurately and repeatably measure them in the field, as well as the amount and relevance of existing scientific literature pertaining to each. The Panel concluded that it was possible to identify PHBs based on stream size, channel gradient, and natural non-deformable obstacles.. These three attributes satisfied the objectives of simplicity, objectivity, accuracy, ease of measurement, and repeatability, that can be consistently identified in the field and can be incorporated into a practical survey protocol. The Board then selected three combinations of stakeholder-proposed PHB criteria for these attributes at their 14 February 2018 meeting (WA FPB 2018) and instructed the PHB Science Panel to develop a field study to evaluate the performance

Commented [LP(59]: Red: How will we distinguish between fish absence due to natural barriers vs. non-natural barriers?
Fish presence may be affected by things associated with timber harvest such as culverts, slash accumulations, mass wasting. If this isn't accounted for, it seems like it can become a confounding factor. For example, the last detected fish may be located below an impassable culvert, but the habitat immediately upstream of the culvert doesn't have any natural barriers. If the F/N break isn't flagged in the database with the culver metadata, then it would look like the F/N break was associated with the natural physical habitat rather than the non-natural barrier, which would influence the analysis of PHB accuracy. Maybe I'm missing something, but I think more clarification is needed.

Commented [JW60R59]: Double check to ensure exclusion criteria (e.g. blocking culverts) are addressed in the document. We think they are but need to double check. Might just be in field methods stuff right now???

Commented [MM61]: yellow. What about "permanent natural barriers such as falls and chutes (vs a transient barrier such as wood jams and debris flow plugs).

Commented [LP(62]: Yellow: please define somewhere of these proposals (Table 1). It was important to the Board to determine which of the proposed criteria most reliably identify PHBs in eastern and western Washington. The Board also instructed the Science Panel to stratify sampling by ecoregion and to examine crew variability in identifying PHBs, especially evaluating aspects of field measurement practicality and repeatability (WA FPB August 2017).

Table 1. Three combinations of barrier, gradient, and width PHBs selected for evaluation by the Washington Forest Practices Board.

Type/	Description of criteria
	Criteria 1
Barrier	Gradient >20%, and barrier elevation difference is greater than BFW
Gradient	10% gradient threshold (Upstream Grad>10% and downstream Grad<10%)
Width	2 ft upstream threshold (Upstream BFW <2ft)
	Criteria 2
Barrier	Gradient >30%, and barrier elevation difference is greater than twice BFW
Gradient	Gradient difference >= 5% (upstream grad - downstream grad >=5) and Downstream gradient >10%
Width	2 ft upstream threshold (Upstream BFW <2ft)
	Criteria 3
Barrier	Gradient >20%, and barrier elevation difference is greater than BFW
Gradient	Gradient difference >= 5% (upstream grad - downstream grad >=5)
Width	20% reduction in bankfull width (upstream to downstream width at tributary confluences ratio <=.8)

Methods

Sample Frame and Study Sites

Commented [MM63]: Yellow. Seems theses should be labeled Permanent Natural Barrier, Stream gradient barrier, and minimum stream size. Permanent Natural barrier refers to falls and chutes and require measurements of plunge pool depth and height (both measured from BFW elevation). Stream gradient is the minima over a given distance (e.g. 20% over 30 ft). Stream size, also called lack of living space, is the most difficult and BFW depth could be added (e.g., pools 1 foot deep at BFW elevation) and can sometimes be combined with stream gradient to make PHB from 2 of the criteria.

Commented [MM64]: Green. I have the distinct advantage of not knowing the convoluted history behind this project but operationally, these would not be simple, objective, or accurate. It appears you are obliged to assess these PHBs. A paragraph explaining these would be helpful. I read them and am not sure what the PHB criteria mean let alone apply them in the field. I interpret this as if 1 or more of the three met, it is a PHB. Scaling it to BFW is an odd choice.

Commented [MM65]: Green. No clue what this is.

Commented [MM66]: Green. So BFW <2'? And what about BFW depth?

Commented [TA(67]: Comment from WDFW:

Study Design: There are three primary components of the study design: 1) survey design (i.e., when and where samples are collected), 2) sampling methods (i.e., how fish occurrence and habitat samples will be collected), and 3) analytical methods and model assessment. Unfortunately, it appears that each study design component was developed without regard to the other components. Having a survey design and analytical methods that are commensurate is essential to study success.

Commented [TA(68]: Comment from WDFW:

Sampling Methods: Fish occurrence (and habitat data to some extent) are important. However, the accuracy of the fish occurrence data is of paramount importance. There is a vast literature on electrofishing survey sufficiency and discontinuities in fish geographic distributions that can help address errors, especially false absences. We can be very certain we are underestimating the geographic distribution of suitable fish habitat (at least potentially, in time) and we're certainly failing to sample fish where they occur due to many reasons, but we almost never have a false presence. Given that false absences will be much more ...

Commented [TA(69]: Comment from WDFW:

Survey design: The concepts of spatial balance, randomness (representativeness), and especially rotating panels seem disconnected to the proposed analytical methods. Identifying and agreeing on a ...

To evaluate the accuracy of PHB criteria as a method to identify EOF habitat, a representative sample of study sites must be obtained for applying the criteria. The target population is defined as the set of all currently mapped (modeled or surveyed) fish habitat breaks in streams on forested land in Washington. A sampling frame that matches the target population as closely as possible is needed for unbiased inference. Fish/non-fish stream type break points extracted from the current DNR water type GIS map layer (DNR hydro, watercourses; https://data-wadnr.opendata.arcgis.com/datasets/wadnr::dnr-hydrography-watercourses-forest-practices-regulation/about) is an accessible source of possible study sites. Some of these points are based on field surveys that were concurred through the WTM review process while others are modeled points obtained from a logistic regression model that predicts F/N points based on basin area, upstream and downstream gradients, elevation, and precipitation (Conrad et al. 2003~~,~~; Duke,~~.~~ 2005). Modeled F/N breaks are distributed across the entire state, but modeled points do not necessarily reflect the actual fish distribution and will require additional effort to locate the extent of fish distribution. Furthermore, the 10m digital elevation model (DEM) on which the hydrolayer is based is subject to frame undercoverage (omitted units of the target population) and frame overcoverage (non-target sites erroneously included in the sampling frame). Frame error was found to vary by region, with more undercoverage occurring in western Washington and more frame overcoverage occurring in eastern Washington. To provide the broadest basis for inference, the F/N break points on the DNR hydrolayer, which includes a combination of concurred (survey based) and modeled points, will serve as the sampling frame. This hybrid approach to the sampling frame incorporates existing information while allowing a broader scope of inference than if only the WTM data were used.

The study design will incorporate spatially balanced sampling. A spatially balanced sample provides a sample that is geographically diverse, which generally means outcomes exhibit less spatial correlation across units (Olsen et al. 2015). When outcomes are less correlated, outcomes are more spatially independent of one another, thus increasing effective sample sizes. Several types of spatially balanced samples exist, including two-dimensional systematic (or grid) samples, balanced acceptance sampling (BAS; Robertson et al. 2013), Halton iterative partitioning (HIP; Robertson et al. 2018), and generalized random tessellation stratification

Commented [MM70]: Green: Table 1? You are referring to the three PHB types yes?

Commented [MM71]: Green: Your justification in combining them is that you have identified small headwater streams with known or assumed fish. The statistical inference of the sample to the closed population, ideally requires that each sample in the population has an equal chance of being selected.

Commented [MM72]: Green. I assume you are combining them to encompassing a broader set of potential sites (a well-defined closed population) that you are randomly selecting from. If you want to not compromise the statistical inference of the sample to the closed population, then each site must have equal chance of being sampled.

Commented [MM73]: Green. Stratified random sampling by HUC 12?

(GRTS; Stevens and Olsen 2003, 2004). This study will use GRTS sampling approach over the other two approaches, because the R package used to draw the other two types of spatially-balanced sampling (BAS & HIP) is currently not being maintained on the CRAN server for R packages whereas the GRTS package, spsurvey, is maintained by the EPA (Appendix B).

The spatially balanced sample of F/N points will be selected within each regional stratum (eastern or western Washington)[2]. The western region of Washington consists of about one-third of the state but twice the stream density. Given the differences in stream distribution across the state and the different sources of frame error in each region, east-west stratification will be applied to ensure that spatial balance is maintained within each region.

Sampling effort will be apportioned among mapped terminal or lateral F/N break point type (Figure 5) with "soft stratification." In this approach, the point types are not available for each site before the survey, so no sampling frame is available to identify each subpopulation for *a priori* stratification. Survey crews will record the point type at the time of the survey and, when the desired sample size for a point type is satisfied, survey data from this point type will not be collected at subsequent points of this type. Because soft stratification cannot be planned in advance, employing this technique will require some adherence to the spatially-balanced ordered list of sites to ensure that the obtained sample of sites within each point type is also spatially balanced. The point type should be recorded for each site so that inclusion probabilities for each site may be calculated prior to analysis for any design-based summaries such as means and totals. This apportionment will only occur during the initial site surveys. If a site changes from a lateral to a terminal stream over the course of the study, we will not add any study sites to accommodate that change.

Based on an analysis of observed variability in channel gradient and width upstream of last detected fish points from previous CMER studies and existing water type modification forms

Commented [MM74]: yellow. I mentioned at the CMER meeting that I had issues with this. I have no problem not knowing F/N for a given site – if it doesn't fit your sample criteria select another from your spatially balanced design.

The issues to me are: 1) there are a lot of headwater streams that are obvious N (e.g., gradients >40%?) – should they be included? 2) I agree that characterizing EOF for these "Lateral" streams is essential but that is an entirely different barrier criteria because it is related to main stem flood flows. Are defining them separately so that you can do separate analyses on them?

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[2] We considered other finer scale stratification (e.g., geology, channel type, elevation, valley confinement), but these were not logistically feasible and would greatly increase the sample size, cost and time needed to complete the study. The Washington Forest Practices Board also instructed the PHB Science Panel to develop a study plan that specifically included stratification by ecoregion.

(Appendix B) we propose to determine the location of last detectable fish at 160 sites in forested watersheds in eastern Washington and 190 sites in forested watersheds in western Washington[3], and measure the habitat characteristics (gradient, channel width, barriers) using a long-profile survey 660 ft (200 m) above and 660 ft below the last detected fish. The last detected fish locations will be determined during each sampling event via electrofishing surveys. The corresponding habitat surveys surrounding the located last fish point are expected to provide the data necessary to evaluate differences among PHB criteria across the state and within the eastern and western Washington regions. Data collected with consistent methods and crews might have lower variability than the data we used to estimate sample size.

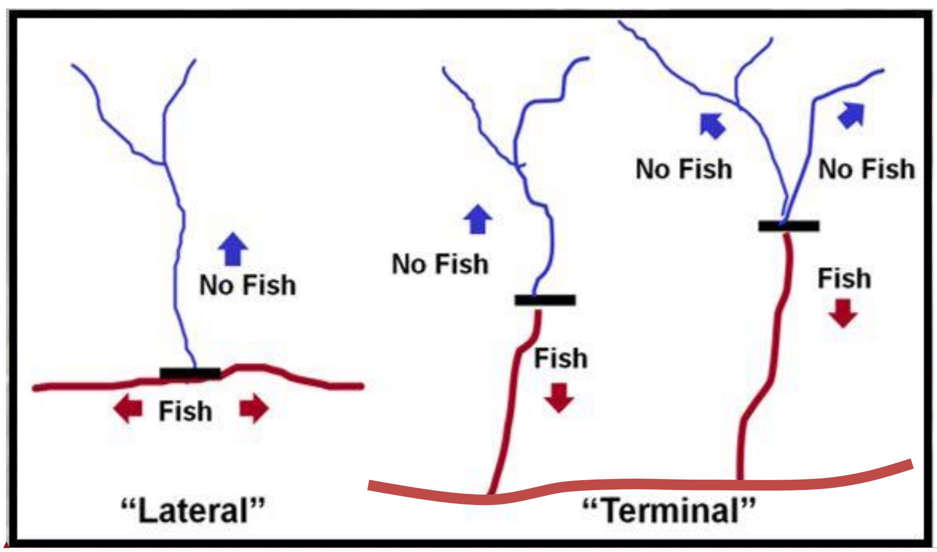

Figure 5. Schematic diagram of lateral versus terminal upstream limits of fish occurrence within streams. The black bar(s) indicate the location of the uppermost fish (Fransen et al. 2006).

Commented [MM75]: Red. Seems arbitrary. Why not do a rapid assessment of PHB starting from known fish to the last detected fish? It seems *the most valuable information you will gather is characterizing the set of PHBs that are downstream of the last fish*. This is the set of potential barriers that you know were passable. You might find that going above the last fish for 200 m might put the crew crawling up 60% gradient with a backpack shocker – which is a waste of sample time, not to mention a potential safety issue.

You may also find more extreme PHB downstream of fish than upstream of the last fish 😉

Commented [JW76R75]: Confirm that this is habitat assessment and not distance over which we were looking for fish. Need to specify that this distance is based on observed variability work (Cole, Walter, etc.) done in the past.

Consider 'basin area' (flow/stream size) influence on PHBs. Recognize that presence of fish upstream from a given feature doesn't mean that the specific feature was traversed/passed in its current state by the current population.

Most useful information RE what fish can/can't traverse will come from what we observe over the course of sampling.

Farther we go downstream from last fish location the less informative that habitat info may be due to the increased potential for that fish population to be potentially an isolated one.

Commented [LP(77]: Yellow: That's a lot of feet above and below in potentially challenging terrain. There should be some rationale for why this is the right distance.

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Commented [MM78]: Green. Added the main stem to the terminal. This was the point I was trying to make (ever so poorly) at the CMER meeting. Now that I have had time to think about it a little more, I could see the value of separating lateral and terminal in the analysis.

[3] The recommended sample size includes sites in addition to the minimum number calculated to meet the specified statistical requirements. This allows for site attrition over life of the project.

Site Identification

The DNR Hydro Watercourses hydrography data layer contains stream channel locations across the state. Stream lines are kept as segments with properties about each segment stored as attributes. Segments are divided at intersections with other stream segments and any place where their recorded properties change (e.g. - fish use/non-fish use). The points at which this classification changes from fish (Type F) to non-fish (Type N) will be extracted from this hydro layer. The properties of the fish use segment below the break are retained with those data points and stored in the new point layer. The attributes (properties) of interest for this study include the bases of the fish use determination, such as whether it was a segment modeled as likely fish habitat, a concurred legacy determination, from a water type modification form, etc. Another attribute is whether that determination was based on biological information (fish observation or electroshocking findings) or on habitat assessment. Such information will be important for locating the optimum survey starting location but will not be used for the purposes of selecting sample streams.

The F/N break points are intersected with the East/West Washington polygons to assign them an East/West attribute. (Points will also be intersected with the DNR Ecoregions polygon layer to assign them an Ecoregion attribute. However, that attribute will be used as a covariate in post-hoc analyses rather than as a stratification variable.) The point layer will be subjected to the GRTS spatial randomization procedure, which will assign a sequence number to each point. The points to be inspected for this study will be selected from each side of the state in the sequence assigned. As points are discarded according to our rejection criteria (below), the next sequential point will be added to the sample population. In this way, spatial balance and random validity should be maintained. This will be verified visually by tracking the current sample selection on a map.

In practice, batches of points will be selected and assessed for suitability, access permission, and field inspection to facilitate the sample set delineation. These batches will ensure that more points (streams) are ready to be sampled (and even perhaps initially sampled) than are actually needed in case selected points are rejected during the first study season. However, the points will always be sampled and analyzed with the priority of their sequence in order to preserve the randomness and spatial balance of the selection

The F/N break point will identify the stream to be sampled, not necessarily the sample starting point. The starting points will be the highest known fish location for that stream based on any available information that can be obtained about that stream. The GIS layer contains some information, such as the typing basis. Other information may be obtained from landowners, tribal entities that monitor that stream area, and other local experts. In the case of tributary streams that have no reliable fish observations, the electrofishing survey will start at the confluence of the subject stream with the known fish-bearing mainstem stream. The initial survey will determine lateral versus terminal status of the selected tributary for site allocation purposes during site selection.

Site Rejection Criteria

Some potential study sites will be excluded from the sample population due to unforeseen circumstances. During the site selection and field validation task, study sites may be dropped as follows:

- Sites where the last upstream fish is associated with a man-made barrier;
- Streams showing evidence of recent (e.g., within ~~three to~~ five years) debris flows through the subject stream;
- Sites where we cannot obtain landowner permission for the full survey length;
- Sites that we do not have safe access to;
- Other reasons determined by project team.

In every case that a site is excluded from the sample, the reasons will be thoroughly documented.

Sampling Frequency and Season

Field surveys (electrofishing and habitat) will be conducted during the spring/early summer and

Commented [MM79]: red It is critical that the last fish sampled got there on their own and were not planted. Although rare, it is possible. If there is evidence that fish were planted, then the site should be excluded from the analysis.

Commented [JW80R79]: Regardless of stocked or not or species at LF still good information on what is limiting those fishes from moving further upstream. Also, no difference in how these sites are treated from a regulatory perspective.

Commented [LP(81]: Yellow: I'm a little concerned about not distinguishing between sites where there has been recent timber harvest (upstream or downstream) and sites where there hasn't been recent harvest since that has the potential to affect fish distribution.

How will the influence of land use be addressed?

the late fall/early winter sampling periods (seasons). These two high flow periods were chosen because they represent the most likely time periods for fish to be found at their highest point in the stream network, and therefore should be adequate to evaluate seasonal differences in the upper extent of fish use. While summer sampling may be beneficial to compare seasons, due to the low flows typical of summer, it is unlikely that fish would move higher into the system in that season (Cole and Lemke, 2006).

Commented [LP(82]: Green: should add approx. dates

All sites will be surveyed every year during spring/early summer (current protocol electrofishing survey window of March 1 to July 15) for three years to examine inter-annual changes in last detected fish. To evaluate seasonal changes in the location of the last detected fish, the sites that can be accessed in the fall/winter high-flow season will also be sampled on a rotating panel basis. One quarter of the sites will constitute the fixed portion of the panel and will be surveyed every fall/winter, and the remainder will constitute the rotating portion. One third of the rotating portion will be sampled each year in addition to the fixed portion. The fixed portion of the panel will consist of the full count of sites from Table 2, while the rotating portion counts will vary depending on site accessibility. The survey timing within both sampling periods will be determined through consultation with regional experts to optimize the timing based on local hydrology and fish life history and resurvey timing will be consistent (within two weeks of the original survey date) across years.

Commented [LP(83]: Yellow: fish distribution in some places may be affected by max temperatures by mid-July

Commented [MM84]: Green. You may also be limited by the weather; shocking after a storm is preferred to shocking during one!

Table 2. Overall sampling schedule by calendar year and season 2024 to 2026. All sites will be sampled in spring to early summer (March 1 to July 15) with the seasonal fixed and rotating panel being resampled in fall to early winter high flow period (dates determined through consultation with regional experts). A pilot study sampling 15 sites in eastern and 12 sites in western Washington was completed in September of 2018.

Sampling Event	Pilot year (2018)	Year 1 (2024)	Year 2 (2025)	Year 3 (2026)
Spring to early summer		160 eastern Washington 190 western Washington	160 eastern Washington 190 western Washington	160 eastern Washington 190 western Washington

Late Fall/Winter Fixed Panel Sampled All Years (same sites)	27 to test methods	40 E WA 48 W WA	40 E WA 48 W WA	40 E WA 48 W WA
Late Fall/Winter Rotating panel, Sampled Only in Single Season		40 E WA 48 W WA	40 E WA 47 W WA	40 E WA 47 W WA
Reporting	Pilot study report	Annual report	Annual Report	Final Report

Protocol Electrofishing and Habitat Surveys

The protocol electrofishing and habitat survey will provide a complete data set to inform the PHB and associated analyses. Protocol electrofishing surveys will be conducted to determine the location of the last fish at each survey event. We will then conduct channel habitat surveys up- and downstream of that last fish point to provide data for addressing the study questions. The channel survey data will be used to partition the study reach into variable-length stream segments that are scaled to lengths of homogeneous habitat features within the long-channel profile. The length of segments will be based on changes in gradient and channel width that are associated with inflection points and/or changes in habitat features (e.g., vertical and non-vertical obstacle). Vertical and near-vertical obstacles will be captured as individual segments, as such features will have some segment length associated with them.

Prior to sampling a site, the project team will review existing information from any available sources on access, previous location of last detected fish and habitat data, and obtain landowner permission for access and sampling. In determining the upstream extent of fish distribution, multiple upstream segments may be available for survey. When this situation occurs, the selected surveyed segment will be the mainstem channel, defined as the stream segment with the largest contributing basin area upstream from a tributary junction (should have largest bankfull width, most flow, etc.). Where basin area upstream from a junction appears approximately equal, rely on additional on-site metrics such as bankfull width and/or flow to determine upstream direction of survey. Stream segments not included in the hydrolayer may be encountered when moving upstream. These stream segments will be included in the survey process in accordance with the above criteria.

Commented [LP(85]: Yellow: Should probably be discussing potential mortality, just for the sake of acknowledging that studies like this, and electroshocking for water typing are not entirely benign.

Commented [LP(86]: Yellow: but what if the segment with the largest contributing area is steeper and more likely to have a shorter distance to a barrier?

Field crews will use modified DNR protocol electrofishing surveys with the intensity consistent with methods being developed for FHAM to determine last detected fish (Figure 6a). Water temperature (to the nearest 0.1 °C), conductivity (micro-Seimens), and electrofishing setting (e.g., voltage, frequency, pulse width) will be recorded at the beginning of each electrofishing survey. The GPS coordinates of each last detected fish location will be recorded, and the location will be flagged and monumented with a marker including the survey date on an adjacent tree. The fish species and approximate sizes will be recorded. Electrofishing surveys will continue from the last detected fish point upstream to the end of default physical fish criteria (end DPC point). In the event the last detected fish is found at the end of default physical criteria, electrofishing will continue 660 feet (upstream) to align with the extent of the detailed habitat surveys. We will also record electrofishing survey time (shock seconds). Coarse scale habitat data will be collected on the full extent of the e-fishing survey. These data will include channel gradient, bankfull width, wetted width and confinement within unequal length segments of relatively uniform habitat character.

An intensive longitudinal thalweg and water surface profile habitat survey will be used to assess key habitat attributes (i.e., gradient, bankfull and wetted width, water depth, substrate size composition, and height of channel steps) below and above last detected fish (Figure 6b). A previous study of variability on the upper limits of fish distribution in headwater streams suggested that over 90% of the interannual variation in the last detected fish location occurred in less than 200 m upstream and downstream of the last detected fish location (Cole et al. 2006). Therefore, we will use a distance of 660 feet (200 m) below and 660 feet above the last detected fish as our intensive habitat survey reach. The crew will measure 660 feet (horizontal distance) downstream from the last detected fish point to determine the beginning point for the intensive stream habitat survey.

The intensive habitat survey involves surveying the streambed elevation along the deepest portion of the stream (the thalweg), yielding a two-dimensional longitudinal profile of streambed elevations. This has been shown to be a reliable and consistent method for measuring change in stream morphology and fish habitat independent of flow (Mossop and

Commented [MM87]: Yellow. I assume single pass and skipping pools when appropriate? A little more detail on your shocking protocol would be welcomed or provide a reference to the modified DNR protocol.

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Commented [MM88]: Yellow. Are these necessary? This will just slow the crew down and these data will not be that meaningful for defining PHB. You could use the conductivity to check your shocker settings or simply put your finger in the water!

Commented [MM89]: Yellow. This is a fish/no fish binary variable so at a minimum, all you really need is species to confirm presence – e.g. don't even have to net it -a flash of a fish will do. You might determine fish presence without the need of using the shocker, in which case, you can just keep walking upstream.
At the next level, relative count might be useful to say something about relative abundance (so then need to measure the pool width and depth. Size categories might be as simple as . <50, >50, >100 mm. Fish abundance and size would be most critical at or near for EOF. You could probably get all the information you need without the need of putting them in a bucket. In addition, since you will be repeat sampling, it might be good to have the voltage just enough to turn them so minimize your morts.

Commented [MM90]: Yellow: Are these defined in this document? If not, please include either a table or a brief discripton.

Commented [MM91]: Yellow. Is this necessary? I don't see how this time consuming effort contributes to describing PHBs.

The most important channel measurements are associated with the three types of PHB and the gradient features as ...

Commented [LP(92]: Yellow: I think that valley gradient should also be determined at some point, and perhaps distinguish between valley confinement and channel confinement.

Commented [MM93]: Yellow. What about bank undercut? A flag for an unshockable section? Weather conditions? These are issues that reduce electrofishing success in these small but complex streams.

Commented [MM94]: Yellow. But isn't this one of your objectives? It seems circular to modify your protocol assuming you'll reach the same conclusion. I've seen it where there was 500' between fish presence with poor ...

Commented [LP(95]: Green: This is what I was looking for earlier, might want to move it earlier in the doc.

Commented [MM96]: Red. I would suggest that the intensive measurements are not necessary to achieve your objectives. Collecting the data used to create Figure 7 is really all that is essential to answer your questions, no? T ...

Bradford 2006). We will also be recording water surface heights because surface levels are what are important to fish with regard to obstacle heights. Survey measurements will be taken every ten feet, and at any significant inflection points in topography or planform to be sure we capture all changes in thalweg topography and gradient. A laser range finder mounted on a monopod and a target on a second monopod will be used to collect distance and elevation data. All data will be entered into a computer tablet in the field. Measurements and observations at each point will include horizontal distance and slope between survey points, water depths, wetted widths, bankfull width, dominant substrate (e.g, sand, gravel, cobble), large wood, habitat feature (e.g., pool, riffle, cascade), and general characterization of flow and water conditions. Water surface elevation will be calculated after the survey from the bed elevation plus the measured water depth. For steps and potential migration barriers, the crew will record whether the step is formed by wood, bedrock, or another substrate. The presence of wood is particularly important because wood-formed barriers and obstacles are considered deformable ~~barriers~~ and are not PHBs. Crews will also note whether flow is continuous or intermittent, the presence of beaver dams, groundwater inputs, and any other unusual features (e.g., tunneled or sub-surface flow) that could influence fish distribution. Because sites will generally be in small, constrained streams that are unlikely to change significantly throughout the sampling year, it is likely that the habitat survey data for each stream will only need to be collected once each year with the spring sampling effort. The survey will be repeated annually to ensure we have a complete survey 660 feet above and 660 feet below the last detected fish found during each sampling event (Figure 6c). A similar protocol based on Mossop and Bradford (2006) has been used to survey barrier removal projects on small streams throughout the Columbia River Basin.

Evaluations of various regional stream habitat survey protocols have demonstrated that with *well-trained* field crews, measurement error is small relative to naturally occurring variability amongst sites (Kershner et al. 2002; Roper et al. 2002; Whitacre et al. 2007). Therefore, all crews will participate in a three to five-day training course each year prior to initiation of spring sampling to ensure consistency among crews in determining last detected fish, surveying habitat features (long-profiles), and data collection. Moreover, to quantify variability among

Commented [MM97]: Green. This is the essential component that should be measured from the beginning of the survey.

Commented [MM98]: Green. I am sympathetic to the crew dragging around this equipment with a shocker and extra battery, staff or tape, and an iPad. This could be done by giving each crew member a range finder and putting a reflector on their helmets. Part of the difficulty is that site distances can be limited so the segments might be rather short (e.g., 5 m) in places, and not associated with any inflection point.

Commented [MM99]: Green. Do you think you could get away with the GPS in an iPad (with a signal booster such as a Garmin Glo) with some mapping program such as Avenza (tracking mode, add points for survey points associated with a custom survey form)? I think that the methods described here are fairly time intensive (that's 66 points to the EOF) to obtain a level of detail that might not be necessary.

Commented [LP(100]: Yellow: I think that fish presence is partially controlled by channel hydraulics. Pool availability and characteristics are important I think, i.e. the lower the "quality" of pool habitat, the lower the likelihood of fish presence. For example, is it a pool where fish can readily persist in in high and low flow, or are water velocity and/or turbulence at high flow volumes too great for fish to persist in those pools? And at low flows, are pools too shallow to provide enough resting/hiding cover?

So I think there should be measurements that get at pool frequency, morphology and hydraulics. I suggest estimating pool volume, residual pool depths, and hydraulic radius (cross sectional area of flow/wetted perimeter). I say hydraulic radius because pool volume by itself probably isn't enough; there can be a wide shallow pool with the same volume as a deep, narrow pool, but the hydraulics will be very different. Not sure how to accurately estimate high ...

Commented [LP(101]: Yellow: what can realistically be done with this qualitative information? If it may be influencing fish distribution, it should be quantified, if not, or if it can't be used in an analysis later on, then why waste the time?

Commented [LP(102]: Yellow: Is there going to be a quality assurance plan to address protocols, accuracy, precision, bias, representativeness, comparability, completeness? Probably should since the overall accuracy of the analysis of the predictive physical parameters will hinge upon the quality of the data.

Commented [MM103]: yellow. Please consider "transient natural barrier" and an important topic to teach the crew.

Commented [MM104]: Green. I would prefer to say that you will document overwinter changes by repeat sampling in the spring of each year.

crews in conducting longitudinal surveys, we propose that 10% of all sites sampled each spring should be resampled by other crews every year (i.e., 10% of the sites will have three replicate surveys). Since variation in stream flow during subsequent surveys should not affect the longitudinal bed profile, we don't expect flow changes to contribute to variability observed among crews in these resurveys.

Commented [MM105]: Green. 35 sites? Could you do this at the end of the training session? If you have 4 crews, take 4 days and do a round robin. Then assess if the variability among the crews is acceptable. This is another reason to simplify your protocol.

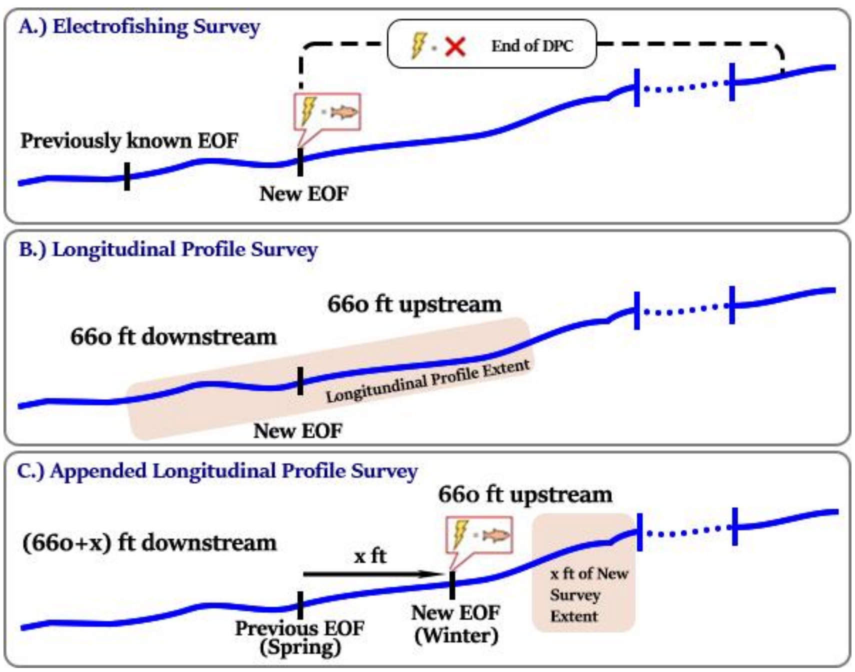


Figure 6. Components of field surveys demonstrating: (A) the extent of the protocol electrofishing survey to determine end of fish (EOF) point, (B) the range of the initial longitudinal profile habitat survey associated with the initial EOF point, and (C) an example of how the longitudinal profile survey would be appended if follow up protocol electrofishing surveys identify a new EOF point (adapted from PHB Science Panel 2019).

Reach- and Basin-Scale Explanatory Variables Derived From Office and Remote Sources

We will also collect data on several other factors that are thought to play a role in last detected fish point and identification of PHBs from sources other than field data. These include: elevation, aspect, drainage area, distance to divide[4], valley width, annual precipitation, channel type[5], riparian stand condition[6], whether last detected fish and PHB is at a mid-channel point (mainstem or terminal) or confluence (tributary or lateral tributary), dominant drainage area geologic competence category[7], stream order, and whether a stream is accessible to anadromous fish or only resident fish. Many of these variables will be derived from existing GIS data layers. Drainage area, distance to divide, and valley width are important because they, combined with annual precipitation, are related to flow and stream size. The local geology around the stream determines whether stream substrate tends to consist of hard, resistant, larger particles or friable, fine-grained substrates, which have been shown to influence fish distribution (Gresswell et al. 2006; Torgersen et al. 2008).

Commented [MM106]: Yellow What about regional weather data such as precipitation - especially prior to sampling? Also, the severity of the summer drought. Even the nearest flow records might prove useful. Ideally it would be discharge but on a practical basis, regional trends in expansion / contraction might correlate with extremely wet or extremely dry weather patterns.

The regional geology (parent material) might influence steam response to storm – e.g., flashy streams.

Data Preparation

Physical attribute and fish presence data will be organized by site and variable-length segment. To prepare data for analysis, the stream profile will be divided into variable-length homogeneous segments, and each segment will be populated with a suite of segment-scale physical attributes and fish presence or absence. Variable-length segments will also be populated with associated basin-scale attributes that will be derived from GIS. Other basin-scale characteristics will be included for each site. Measures such as gradient and channel width can also be used to form threshold variables that can be assessed as predictors of segment-level fish presence.

Additional data sets to assess changes in distribution over time will be developed. The variation across seasons will be assessed by examining the maximum distance among last fish points observed across seasons within a year for each site. Similarly, the range of last fish points for each of the two seasons will be calculated across years to examine variation across years within

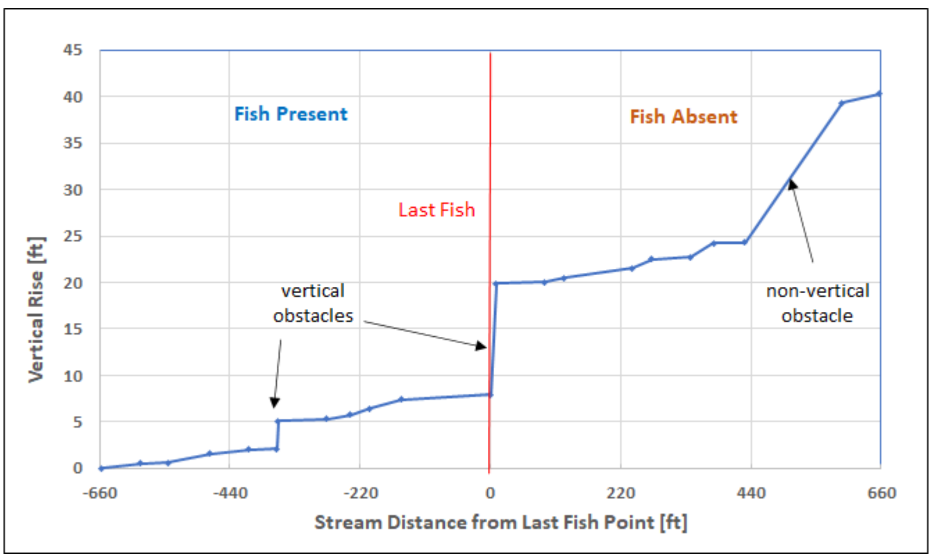
[4] Palmquist (2005) found distance to divide to be less variable and more reliably calculated than basin area
[5] Montgomery & Buffington, 1993
[6] Watershed Analysis categories, WA DNR 1997
[7] Competent/Incompetent, per McIntyre et al. 2009

each season.

Data Analyses

Data Exploration, Summary Statistics, and Initial Tests

After data preparation is complete, initial data exploration will include graphical examination of habitat metrics for segments within a site and for segment means of physical characteristics for each site (Figure 7). Distributions of physical attributes for variable-length segments at a site can be compared for segments with and without fish by and across sites. The length of segments will be based on changes in gradient and channel width that are associated with inflection points and/or changes in habitat features (e.g., vertical [falls] and non-vertical obstacle [steep cascade]). Criteria for classifying variable-length segments and obstacles will be derived during post-hoc data analysis using linear regression methods similar to those described by Tompalski et al. (2017). For seasonal data, physical attributes at each site may be summarized by region (east or west), point type (lateral or terminal), and by season (spring or fall/winter).



Commented [JK107]: GREEN: I am excited by the use of the Random forest methods and am curious if this method will also shed some new light on the suggested criteria for PHB.

Commented [TA(108]: Comment from WDFW:

Analytical Methods:
Methods such as Random Forests will likely be appropriate, but I'm confused by the very limited number of predictors proposed, a priori east-west stratification, and training-testing data splitting. These choices make very poor use of the strengths of methods such as Random Forests. In particular, different models for east and west and splitting data into training and testing data practically ensures that none of the models will work well.
We were glad to hear that you had consulted with a statistician to provide input on statistical design and analysis, and agree that this approach will benefit study design and outcome. Can you develop specific questions for the statistician, rather than prescribing (sometimes inappropriate) methods (as appears was done here)? Given the data and methods, and since the fish assemblages and types and nature of PHB are more similar than different, perhaps it would make sense to include in the model an East-West (i.e., location dummy predictor) and other similar predictors (such as surface geology, ecoregion, an index of fish abundance, etc. if you cannot develop a reasonable conceptual model to identify predictors). This approach would result in a larger sample size and improved statistical power.
Can we use cross-validation methods to assess the model(s), rather than training-testing data splitting? I strongly suspect you can and should, given the iterative methods proposed (e.g., random forests, etc.). Do you really need to be selective about which predictors work best, since the modeling methods sort that out for you? I suggest using cross-validation assessments provided by the analytical program because that's a primary reason to use methods such as Random Forests – they cross-validate as the models are built. But, again, perhaps posing some question to the statistical consultant (rather than prescribing methods, as we believe was done here) could provide improvements.

I'm confident that the predictions of PHB can be substantially improved relative to those currently used. However, I'm not sure the current effort will result in much improvement. Moreover, much of the uncertainty in PHB locations and effects is complex. Geographic distribution of fish is driven largely by temporally variable fish abundances. Also, fish habitat suitability and even the locations and permeability of many barriers to upstream movement differ among years. Addressing uncertainty while meeting our conservation and restoration goals might be more important or more successful than addressing the limitations of the PHB models.

Commented [MM109]: Green. Stream gradient

Figure 7. Schematic of channel long-profile survey showing variable-length segments (i.e., distance between inflection points) and associated vertical and non-vertical obstacles.

PHB Classification Methods

The primary goal of this project is to identify PHBs associated with EOF habitat using a suite of physical channel features and basin characteristics (Research Questions #3, #4, #7, and #8). Three sets of classification criteria proposed by the Board will be assessed (see following section), and an independent set of criteria will be developed with statistical tools for classification. Possible statistical techniques include classification trees (Breiman et al.1984), generalized linear models (McCullagh and Nelder 2019), linear discriminant analysis (Tharwat et al. 2017), and random forests (Cutler et al. 2007, Trigal and Degerman 2015). Random forest methodology is a nonparametric approach used for classification and prediction and can identify important predictor variables among a large suite of possible covariates even when those covariates are highly correlated (Cutler et al. 2007, Kubosova et al. 2010). Random forest can also bin continuous data into discrete categories as part of the analysis, as opposed to assigning arbitrary bins *a priori*. Cutler et al. (2007) found that random forests had high classification accuracy compared to classification trees, generalized linear models (logistic regression), and linear discriminant analysis. Random forest (RF) classification has been used to classify salmonid habitat in Alaska (Romey and Martin 2021), fish assemblage presence in stream segments in coastal Australia (Rose et al. 2016), and in macroinvertebrate habitat in the Czech Republic (Kubosova et al. 2010). Random forest methods have been extended to boosted random forests (Ko et al. 2015, Mishina et al. 2015) which features more memory-efficient calculations. When classification covariates are impacted by spatial and/or temporal correlation, binary mixed model forest (Speiser et al. 2019) or generalized mixed effects random forest (Fontana et al. 2021, Seibold et al. 2019) can account for these sources of correlation.

Random forest classification will be applied to the binary indicator of fish presence within each of the variable length segments to model PHBs as a function of physical and basin characteristics. Separate random forest classifications may be applied to eastern and western

Commented [MM110]: Yellow. Again, the most valuable information obtained will be the PHB downstream of the EOF and how they compare with PHB upstream of EOF for a given stream.

Commented [MM111]: Yellow. Sure, it's a multivariate response – each of the 3 barrier types has multiple variables needed to describe it. However, I would suggest avoiding a data mining exercise. Rather, the barrier types and the variables to characterize them are known (please see previous comment).

sites and for lateral and terminal points to identify influential variables independently in each system. The data will be split into training and testing data sets to assess the performance of the random forest classification. A random forest model will be developed from the training data set and then applied to the test data set to assess classification. Classification performance metrics will include the overall percentage of PHBs that were correctly classified, sensitivity (proportion of presences correctly classified), specificity (proportion of absences correctly classified), kappa (a measure of agreement computed across presences and absences, Cohen 1960), and the area under the receiver operating characteristic curve (Fawcett 2006). The final model will be applied to the entire sample of points to obtain indices of fish presence.

~~Board-Proposed PHB~~ Performance Evaluation of Board-Accepted PHB Criteria

The three sets of classification criteria proposed by the Washington Forest Practices Board (Research Question #10) will be assessed in two different ways. The first method will be to compare frequencies that the various criteria occur above and below the last fish. The performance of each type of PHB variable (ie – gradient, obstacle characteristic, channel width) and criterion within the three proposed criteria sets will be assessed individually and then in combination with the others. The second method will use random forest statistical analyses, which may be better suited to capture interactions between or combinations of the proposed attributes that perform well. ~~with random forest methodology (Research Question #10)~~. ~~Each proposed criteria set will be assessed by~~ When performing the random forest analyses to address this study question, ~~including~~ only the ~~proposed~~ variables included in the proposals will be used in the ~~random forest~~ model (ie. – without other explanatory variables) and the critical values for each variable identified by the random forest will be compared to the proposed values in each criteria set.

The data will be split into training and testing data sets by randomly selecting EOF points into each group. The training EOF points will be used to develop the random forest model, and the testing data set will be used to assess the performance of the model to classify variable length segments as above or below the last fish point. PHB criteria provided by the Washington Forest

Commented [LP(112]: Red: I would like to see a priori decision criteria established for the evaluation.

Commented [JW113R112]: Does criteria here specifically mean PHB criteria (metrics) or is he talking about criteria for identifying specific sties as 'training' data??? GET CLARIFICATION FROM PATRICK?

Commented [LP(114]: Green: good

Practices Board can be similarly assessed by developing a random forest model for each criteria set and evaluating the performance of each classification.

Pilot Data Analysis

Data from a 2018 pilot PHB study (PHB Science Panel 2018b) that used essentially the same habitat data collection methods as those proposed in this current design were analyzed to demonstrate available analysis tools to identify habitat features associated with the end of fish (Appendix C). Random forest models, including interaction forest models, were applied to habitat covariates obtained from the pilot data to identify important habitat covariates associated with the end of fish. Additionally, random forest methodology was used to assess the Forest Practices Board-proposed PHB criteria. We found that random forest methodology was effective in identifying covariates and predicting segment-level fish presence. Accuracy and sensitivity were improved by applying interaction forest models, which account for strong interactions between habitat covariates. While these models are effective in identifying habitat covariates associated with fish distribution and graphical summaries of model results may provide useful information for determining end-of-fish criteria, random forest methodology does not explicitly identify the habitat characteristic associated with PHBs. We suggest applying random forest models for habitat covariate selection and then applying the selected covariates in an analysis that will help identify the PHB. Possible analysis methods to identify the end of fish habitat as a function of habitat covariates include changepoint analysis (Killick et al. 2012, Muggeo 2008), generalized additive models (Large et al. 2013), or covariate-dependent hidden Markov models (McClintock et al. 2020).

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Interannual and Seasonal Last Fish Variability

Interannual and seasonal variation in the last detected fish locations (Research Questions #1, #2, and #5) will be assessed with linear mixed models or generalized linear mixed models (Bolker et al. 2009). The model may contain classification and continuous covariates that explain seasonal movement, including the season, region (east/west), ecoregion, and point type (lateral/terminal). Random effects for space and time will ensure that standard errors for fixed effects estimates are not underestimated due to correlation. Variance components may

Commented [MM115]: Yellow. One of the simplest but most directly relevant metric is simply the difference in slope distances of the EOF seasonally, and annually. Assessing the magnitude of the seasonal and annual change in terms of PHB characteristics (e.g., lateral sites that were never breached; fall >10 ft etc., slopes with >25% minima over 10 m, etc.) would seem to be very informative. It would also be interesting if you could discern a year effect or a seasonal effect and relate that to precipitation. Also, was an expansion /contraction observed – how strong was it and where did it expand / contract the most and the least?

also incorporate habitat categories for which variance heterogeneity in seasonal movement is observed (e.g., low vs high elevation).

All statistical analysis will be conducted in the R statistical programming language (R Core Team 2021). Random forest modeling will apply the randomForest package (Liaw and Wiener 2002) and generalized linear mixed modeling will be conducted with the glmmTMB package (Brooks et al. 2017).

Physical Changes in Features Originally Identified as PHBs Over Time (Research Question #6)

Repeated measurement of PHB features will be used to assess changes in the physical characteristics of those features over the course of the study. ~~Compare physical features measured among sampling events at locations of the various tested PHBs to assess the degree of change in the parameters defining those PHBs.~~

Effect of Crew Variability on Identification of PHBs (Research Question #9)

Crew-variability testing conducted within this study will provide insight into the ability for multiple survey crews to repeatably identify the same PHBs when implementing FHAM in the field in the future.

Should be decision criteria for this too. For example, a protocol will be determined to be consistently applied if repeated measurements by separate crews differ by less than 10%, on average.

Potential Challenges

Although the methods we propose have been widely used to quantify habitat conditions and identify last detected fish, there are some potential challenges. These include location of sites that meet selection criteria, access to initially identified sites, and access to these sites throughout the two seasons and three years. It is possible that we may not have access to selected sample sites due to issues with land ownership, landowner willingness to permit access, or problems with the road networks. Thus, if a site is not suitable due to access or for other reasons a different site (the next consecutive site number from the initial random selection) would be used to replace the non-suitable site, and the reasons the site is excluded will

Commented [LP(116]: Red: This is where non-measured variables have the potential to cause trouble, which is why I would like to see a better accounting for non-measured factors that may influence fish distribution.

The document addresses it a little on page 22 where it says "Crews will also note whether flow is continuous or intermittent, the presence of beaver dams, groundwater inputs, and any other unusual features (e.g., tunneled or sub-surface flow) that could influence fish distribution." However, I'm not seeing how the evaluation will address other natural and non-natural factors that may influence the evaluation of the accuracy of the selected physical factors as predictors of fish distribution

Commented [JW117R116]: Ask for clarification from Patrick RE what exactly he means when he says, "I would like to see a better accounting…". Keep in mind explanatory variables that we are currently focused on are those that are parts of FHAM. Transient barriers, beaver dams, etc. will all be identified and quantified in the habitat survey… and the presence of these types of features can be identified as a factor within the random forest analysis.

Commented [MM118]: Yellow. A little more here would be welcomed. Like comparing gradient profiles? Changes in Transient natural barriers size, abundance, and distribution?

A few suggestions (not sure where to put them)
If you are going to count the fish captured, maybe a comparison of relative fish abundance and /or their distribution pattern.

Do you anticipate any differences between eastside and westside streams? I would suspect that the eastside has a lot more seasonal Type F streams, which influences which fish are found at the upper extent?

Where there a difference in PHBs by EOF species?

Commented [LP(119]: Yellow: how will this be done?

Also, what if it is found that some parameter has wide variability among observers? What will you do with that data… treat it as normal, or discard it, or…?

be documented. This study is targeted at identifying the features and channel characteristics that limit upstream extent of fish distribution, which should not be strongly dependent on particular land uses or ownership types. Therefore results should have broad applicability despite any site selection biases that may occur. A more challenging scenario would be if accessibility changes between or among seasons and years. For example, forest fires, heavy early or late snow, or road failures could affect repeat surveys at a site. In such cases, we would continue to sample sites during other seasons and years when possible. The recommended sample size includes sites in addition to the minimum number calculated to meet the specified statistical requirements. This allows for some site attrition over life of the project.

An additional challenge with study implementation will be largely financial and could result from underestimating or overestimating the amount of time and cost needed to adequately sample sites initially and repeatedly. Similarly, we need to ensure that the data collected will allow us to answer the PHB study questions. To proactively assess these critical uncertainties, a pilot (feasibility) study was conducted in August of 2018 to test and refine protocols, and estimate the time needed to conduct a survey and collect data at a site (PHB Science Panel 2018b). The pilot study included conducting longitudinal thalweg profile surveys upstream and downstream of known last detected fish points at 27 sites on private, state, and federal forestlands in western and eastern Washington. The analysis of longitudinal survey data from the pilot study demonstrated that PHBs based on gradient, BFW, and obstacles being examined by the Board could be easily determined from the survey data. The field surveys helped identify several modifications to the initial proposed protocol that are needed to assure the proposed and other potential PHBs can be easily identified (e.g., spacing of the survey points, habitat types, minimum habitat length, and substrate categories). It also provided important information on time needed to conduct surveys, which we have incorporated into the study plan and estimated cost to conduct the full validation study.

Another challenge is that this study does not address long-term changes in small streams that may render them unsuitable for fish occupancy, or conversely, may render previously unsuitable streams habitable for fish. At any point in time, some headwater streams are not used by fish

Commented [LP(120]: Yellow: Is it possible for access to bias the evaluation? In other words, is it possible that land ownership can influence land use, which in turn may influence fish distribution—and so where the sites are located may influence the results of the evaluation? I have seen where landowners have denied access for a study, then when the results come out, the landowners have said that the study results are not representative of their lands because they did not include their lands. I think it should be acknowledge upfront whether or not access issues have the potential to influence the results (beyond just reducing the # of sites).

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Commented [MM121]: green. Absolutely. And I think you could reduce the cost, increase the crew's accuracy, and providing all the data you need with a streamlined protocol.

Commented [LP(122]: Green: I think there's higher risk of underestimating the amount of time and cost to collect the data at each site since they are going to be 400m long. Better to overestimate than to underestimate for this study.

during any season of the year due to a blockage, to invasion, or to unfavorable physical conditions (e.g., gradient) in the channel itself. Factors that determine whether small streams can be used by fish are typically related to disturbances such as exceptionally high discharge, landslides, debris flows, and windstorms. Such episodic disturbances are erratic and can be widely spaced in time (decades to centuries), but their overall effect in drainage systems is to create a mosaic of streams suitable for fish occupancy that changes over long intervals (often hundreds of years) in response to local disturbance regimes (Kershner et al. 2018; Penaluna et al. 2018). An important implication of the notion that the potential use of small tributaries by fish can change over time is that while some stream segments are not now occupied by fish, there is no guarantee that they may not become suitable in the future, or that those which are currently habitable will always remain so. This study, however, does not address the expansion and contraction of fish habitat over long time intervals, because the sample time is limited to three years and the methods cannot predict with certainty where and in what form large disturbances capable of transforming a stream segment's ability to support fish will occur..

Expected Results and Additional Studies

Highly precise measurements of stream channel conditions both upstream and downstream of last detected fish locations will provide a nearly continuous dataset of physical stream characteristics within the surveyed area. Thus, we will be able to objectively identify the physical stream characteristics most closely associated with last detected fish. These data will be used to test the different PHB criteria under consideration by the Board in 2018, and also to identify alternative physical stream characteristics that may function as PHBs. We expect that the study will assess the performance of proposed and/or identify alternative PHB criteria for gradient, channel width, and barriers that are most frequently associated with the uppermost of all the last detected fish points found at each stream across the time period of the study. Seasonal and inter-annual sampling will allow us to examine the variation of last detected fish locations across years and seasons, which will help identify PHBs that are consistently associated with the upper extent of fish habitat across years, seasons, and flow conditions regardless of where fish are found on any given day. Because we will be using some sites for

Commented [MM123]: Green. Or flow conditions or low population densities

Commented [MM124]: Green. But it does over short interval and over the landscape. So it has a bit of a substitute space for time if the year effect is not strong and there are regional differences.

Commented [DK125]: Yellow- Will you be able to put sideboards on the kinds of stream morphologies/geologies that are appropriate for PHB testing based on your sampling and call out any that may not meet some of the assumptions (e.g. stream systems that originate with headwater wetlands capable of supporting fish does not meet the assumption that the water is diminishing). Or will the rarer stream system types that are tough to put into an apples-to-apples statistically valid study (and rightly so) go into this category of unexplored information?

Commented [LP(126]: Green: True, but doesn't this make an argument for delineating an uninhabited stream reach as Type F, instead of N, if it appears to be habitable?

Commented [MM127]: Yellow. I would expect that the characteristics of the three PHB types - Natural permanent Barrier (vertical distance, plunge pool depth), Stream gradient (slope minima, length), and minimum stream size (BFW, and BF depth) would be evaluated with suggested metrics to use for DPC possibly by region but at least by westside vs eastside.

Commented [LP(128]: Green: out of the ones chosen to be measured, right?

Commented [MM129]: Yellow. It is worth repeating - I would suggest that "gradient, channel width, and barriers" are actually the three PHB types that you are assessing: channel slope barrier is "gradient", minimum stream size is "channel width", and Natural permanent barriers are "barriers which a WTMF already exists and last detected fish was potentially identified, examining longer-term inter-annual variation in last detected fish may be possible for a subset of sites where last detected fish has been previously identified and monumented. In addition, study sites could be revisited in the future to look at longer-term changes in last detected fish, if desired.

Ultimately, the analysis will provide the distances (upstream and downstream) from last detected fish to the different proposed PHB criteria, if and how that differs among years and seasons, whether one set of criteria performs better in terms of consistently identifying EOF habitat across seasons and years, and whether different PHB criteria should be applied for different regions or should be stratified by other factors. While the focus of the study is to test the three different sets of PHB criteria being considered for adoption by the board, we expect that the analyses will help identify other criteria that might more consistently be associated with the last detected fish and therefore better indicate EOF habitat when integrated with FHAM.

The results should also help inform the protocols for measuring gradient, bankfull width, and obstacles in the field to minimize variability among field crews and assure consistent identification of PHBs. Focus should be placed on specific protocols used to consistently and accurately identify and measure physical stream characteristics, including gradient, bankfull width, barriers, and any other criteria that may be used to identify PHBs in this study.

We will also examine seasonal and inter-annual changes in end of fish locations in headwater streams across the state. For the subset of selected sites where previous WTM data exists we may also be able to assess variability at longer time scales. While this would potentially lay the groundwork for continued monitoring of long-term variability in the upper end of fish distribution, it is not designed as a long-term study on such variability. Depending on results, we may recommend that sites continue to be periodically revisited in the future to examine this longer-term variability, but long-term monitoring is beyond the current scope of this study.

DPC Study Integration

With the electrofishing and habitat surveys for each PHBs study stream continuing up to or beyond the end of current DPCs~~, as described on p 22~~, the PHBs study will yield a data set that can be analyzed regarding the frequency with which fish are found up to the limits of current

Commented [LP(130]: Yellow: Yes, but then need to build a formal process in for evaluating protocols and so that knowledge can be appropriately applied to future protocol edits, e.g. what info will be collected on whether the protocols are adequate and how will that be done?

Commented [LP(131]: Green: Why not monument randomly selected sites, so that our children's children can go back and see if fish are still there (or not there)? Or create a geodatabase of reaches or whatever.

Commented [MM132]: Yellow: are you sure these are described on page 22? It would be nice to have a brief description of them.

DPCs, including how this varies between seasons, years, and geography. The coarse scale data collected during the electrofishing survey will also provide channel profiles and other data for the reaches between EOF/H and end of current default physical criteria that can be analyzed for possible explanations as to what features are limiting fish distributions for those sites where fish use does not extend to end of current DPCs. These data will include channel gradient, bankfull width, wetted width and confinement within unequal length segments of relatively uniform habitat character. The results might suggest appropriate metrics for ~~barriers and NVOs~~~~NVOs~~vertical and non-vertical obstacles that could be used in conjunction with width and gradient to add an element of accessibility to the DPCs, thereby improving their accuracy and utility. ~~–I~~In particular, ~~by reducing~~this would reduce the degree to which the current DPCs, when used on their own in the absence of a protocol survey, predict fish use where there are no fish, and are not likely to ever be.~~the number and rate of "false positives" when using DPCs alone, in the absence of protocol surveys~~.

Commented [MM133]: Green. What is EOF/H?

Commented [MM134]: Green: what's an NVO?

Commented [MM135]: Red: I'm not following your logic here since the absence of fish prior to DPC does not mean it's a false positive. Finding a fish above DPC would be inconsistent with the legal intent.

Commented [JW136R135]: RE FIRST COMMENT: We can re-write this sentence to address this and remove the 'false positive' language.

RE SECOND COMMENT: This is just wrong.

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Appendix A. CMER Workplan and prior science panel study questions

CMER Workplan Water Typing Rule Group Critical Questions

The following are the critical questions of the water typing rule group program this study will address:

CQ 1. How can the line demarcating fish- and non-fish habitat waters be accurately identified?

CQ 2. To what extent does the current water typing survey window capture seasonal and annual variability in fish distribution considering potential geographic differences?

CQ 3. How do different fish species use seasonal habitats (timing, frequency, duration)?

CQ 4. How does the upstream extent of fish use at individual sites vary seasonally and annually?

CQ 5. How does the delineation of the upstream extent of fish habitat change seasonally?

Science Panel Ddocument Study Questions

- Do the PHB criteria provided by the Washington Forest Practices Board accurately capture the EOF habitat when applied in the Fish Habitat Assessment Methodology (FHAM)?
- Based on data collected, what is the most accurate combination of metrics for determining PHB by region or ecoregion?
- Are there differences in PHB criteria by Environmental Protection Agency (EPA) Level III ecoregion, eastern vs western Washington, or some other geographic or landscape strata?
- Are there additional variables (e.g., geology, drainage area, valley width, land use, channel type, and stand age) that could improve the accuracy of existing criteria?
- What is the influence of season/timing of survey on PHB identification?

- What is the typical inter-annual variability in last detected fish and PHBs?
- Can protocols used to describe PHB be consistently applied among survey crews and be expected to provide similar results in practice?
- Answering these questions requires identifying the last detected fish and surveying habitat above and below these points in a random representative sample of streams across the state.

Appendix B. Sample Size Estimation Memo of Jan 4, 2022

Field Code Changed

WEST Inc.
ENVIRONMENTAL & STATISTICAL CONSULTANTS
2725 NW Walnut Blvd., Corvallis, OR 97330
Phone: 541 738 6198 • www.west-inc.com

MEMO

To: Instream Science Advisory Group
From: Leigh Ann Starcevich (WEST, Inc.)
Date: January 4, 2022
Re: Sample size approximation from Eastern WA and Western WA data

The Instream Science Advisory Group (ISAG) is developing a sampling design for surveys of potential habitat breaks (PHB) for fish use. A sample size approximation is needed to ensure that the data collected to assess criteria defined by the Washington Forest Practices Board (Board) for the Fish Habitat Assessment methodology (FHAM) yield useful covariates for PHB modeling. Cooperative Monitoring, Evaluation, and Research (CMER) data from eastern Washington surveys conducted in 2001, 2002, and 2005 were provided by Chris Mendoza. Stream habitat data associated with uppermost detected fish points from concurred water type modification forms for surveys conducted in western Washington between 2016 and 2020 were provided by Weyerhaeuser. These data were used to approximate sample sizes needed to estimate means of PHB model covariates with desired levels of precision and accuracy.

Eastern Washington Data

The eastern Washington data were collected in 2001 by Terrapin Environmental (Cupp 2002) and in 2002 and 2005 by ABR, Inc. Environmental Research & Services (Cole and Lemke 2003, 2006). Channel characteristic metrics included mean channel widths and means gradients for reaches extending up to 100m above and 100m below the last fish point obtained in the 2001 survey. Data for barriers were collected but inconsistencies in how barriers were classified and recorded prevented sample size evaluation specific to barriers. For surveys conducted after 2001, the last fish distance relative to the 2001 last fish was provided. A metric for the maximum change in distance from the 2001 last fish point was calculated for each site. Using the 2001 point as baseline, the range of distances where the last fish was observed during subsequent surveys was calculated and used to inform the sample size approximation.

Data screening was used to limit the data set to a subset of locations with natural habitat breaks. Unscreened data sets included sites where large woody debris jams were found, no surface flow occurred for at least 100m, and surveys were conducted past July 15. The screened data sets eliminated many of these sites. Sites where fish passage was limited by culverts were removed from all data sets. About 46% of the unscreened points were classified as lateral points.

Western Washington Data

Water type modification form data from western Washington were collected between 2016 and 2021 and included gradient and bankfull width metrics for stream segments upstream and downstream of the last fish point. For many lateral points, only the upstream measurements were provided because the point was located on a river mainstem. At these points, data on gradient and bankfull width metrics downstream of the confluence were not always collected, so these points are omitted for sample size calculations based on the downstream metrics. About 70% of the points were classified as lateral points.

WEST Inc.
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MEMO

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Date: January 4, 2022
Re: Sample size approximation from Eastern WA and Western WA data

The Instream Science Advisory Group (ISAG) is developing a sampling design for surveys of potential habitat breaks (PHB) for fish use. A sample size approximation is needed to ensure that the data collected to assess criteria defined by the Washington Forest Practices Board (Board) for the Fish Habitat Assessment methodology (FHAM) yield useful covariates for PHB modeling. Cooperative Monitoring, Evaluation, and Research (CMER) data from eastern Washington surveys conducted in 2001, 2002, and 2005 were provided by Chris Mendoza. Stream habitat data associated with uppermost detected fish points from concurred water type modification forms for surveys conducted in western Washington between 2016 and 2020 were provided by Weyerhaeuser. These data were used to approximate sample sizes needed to estimate means of PHB model covariates with desired levels of precision and accuracy.

Eastern Washington Data

The eastern Washington data were collected in 2001 by Terrapin Environmental (Cupp 2002) and in 2002 and 2005 by ABR, Inc. Environmental Research & Services (Cole and Lemke 2003, 2006). Channel characteristic metrics included mean channel widths and means gradients for reaches extending up to 100m above and 100m below the last fish point obtained in the 2001 survey. Data for barriers were collected but inconsistencies in how barriers were classified and recorded prevented sample size evaluation specific to barriers. For surveys conducted after 2001, the last fish distance relative to the 2001 last fish was provided. A metric for the maximum change in distance from the 2001 last fish point was calculated for each site. Using the 2001 point as baseline, the range of distances where the last fish was observed during subsequent surveys was calculated and used to inform the sample size approximation.

Data screening was used to limit the data set to a subset of locations with natural habitat breaks. Unscreened data sets included sites where large woody debris jams were found, no surface flow occurred for at least 100m, and surveys were conducted past July 15. The screened data sets eliminated many of these sites. Sites where fish passage was limited by culverts were removed from all data sets. About 46% of the unscreened points were classified as lateral points.

Western Washington Data

Water type modification form data from western Washington were collected between 2016 and 2021 and included gradient and bankfull width metrics for stream segments upstream and downstream of the last fish point. For many lateral points, only the upstream measurements were provided because the point was located on a river mainstem. At these points, data on gradient and bankfull width metrics downstream of the confluence were not always collected, so these points are omitted for sample size calculations based on the downstream metrics. About 70% of the points were classified as lateral points.

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MEMO

To: Instream Science Advisory Group
From: Leigh Ann Starcevich (WEST, Inc.)
Date: January 4, 2022
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Sample Size Approximation

Estimated means of channel characteristic metrics and change in last fish locations among years were used as the basis for the sample size approximation. Let z reflect the quantile of a standard normal random variable for a given Type I error rate (α). For $\alpha = 0.10$ we have that $z = 1.645$. Let d be the maximum absolute error (i.e. confidence interval half-width), let r be the relative precision of the estimate, and let γ be the coefficient of variation (CV). The coefficient of variation is a standardized measure of precision calculated as the standard deviation (SD) of the outcome divided by the mean of the outcome (Thompson 2002). The sample size approximation formula below is applied with the mean and standard deviation for each outcome of interest. The sample size needed to obtain an estimate that is within 100*r% of the true mean with probability 1 - α was calculated. In other words, the confidence interval half-width of the mean should be 100*r% of the true mean. The sample size to accomplish this goal is based on a normal approximation and calculated as:

$$n = \frac{z^2\gamma^2}{r^2}.$$

For each outcome of interest from the eastern Washington data sets, the coefficient of variation was computed from the mean and standard deviation of the screened (Tables 1 through 3) and unscreened (Tables 4 through 6) data, and sample sizes were approximated for relative precision values of 0.10, 0.15, 0.20, and 0.30. Variation was slightly higher in the unscreened data set, resulting in slightly larger sample sizes. For the eastern data, the coefficients of variation were higher for terminal points than for lateral points for the upstream reach gradient, reach gradient difference, and maximum change in distance (Tables 2 and 3, Tables 5 and 6). The coefficients of variation were higher for lateral points than for terminal points for downstream reach gradient and downstream bankfull width.

Similar results were observed for the western Washington data. For estimation of mean channel metrics across point types, coefficients of variation ranged from 0.69 to 0.79 for reach gradient metrics and for the bankfull width above the point. However, bankfull width measured below the last fish point was less precise than in the eastern Washington data set with a CV of 1.28 (Table 7). The precision for the gradient difference was similar to that observed for the eastern Washington data with coefficients of variation near or above one. For the western data, the coefficients of variation were higher for terminal points than for lateral points for the reach gradient difference (Tables 8 and 9). The coefficients of variation were higher for lateral points than for terminal points for reach gradient metrics and the downstream bankfull width. The higher variability in these metrics suggest larger sample sizes are needed for precise estimation of means. While mean estimation of channel characteristics is not the ultimate inferential goal, we assume that samples large enough to provide information on the range of values for each of the potential PHB modeling covariates will yield a useful data set for modeling.

The maximum change in distance from the eastern data was highly variable and generated large sample sizes for levels of desired precision. The difference in reach gradient exhibited high variability across both the eastern and western data sets, and sample sizes needed for precise mean estimation are large. To obtain relative precision of 0.15, the required sample size is nearly double that calculated for relative

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precision of 0.20. Note that the sum of the sample sizes calculated for lateral and terminal points generally exceeds the sample size calculated from data pooled across point types. This indicates that overall sample sizes may need to be larger than indicated by the pooled analysis to achieve the same level of precision for means of channel characteristics for lateral and terminal points.

Table 1: Estimates of means, standard deviations, and coefficients of variation from *screened eastern WA data pooled across point types* with sample size approximations for four levels of relative precision.

Outcome	n	Est. Mean	SD	CV	$r =$ 0.10	$r =$ 0.15	$r =$ 0.20	$r =$ 0.30
Reach gradient (%) above LF point	193	21.56	13.98	0.65	114	50	28	13
Reach gradient (%) below LF point	161	10.31	6.73	0.65	115	51	29	13
Reach gradient difference (%)	161	9.96	11.19	1.12	341	152	85	38
Bankfull width (m) above LF point	197	2.14	1.41	0.66	117	52	29	13
Bankfull width (m) below LF point	174	1.84	1.35	0.74	146	65	37	16
Maximum change in distance (m)	121	73.26	186.34	2.54	1751	778	438	195

Table 2: Estimates of means, standard deviations, and coefficients of variation from *screened eastern WA data at lateral point types* with sample size approximations for four levels of relative precision.

Outcome	n	Est. Mean	SD	CV	$r =$ 0.10	$r =$ 0.15	$r =$ 0.20	$r =$ 0.30
Reach gradient (%) above LF point	67	24.03	12.36	0.52	72	32	18	8
Reach gradient (%) below LF point	53	8.30	9.25	1.11	336	149	84	37
Reach gradient difference (%)	53	18.30	10.77	0.59	94	42	23	10
Bankfull width (m) above LF point	74	1.42	0.79	0.55	83	37	21	9
Bankfull width (m) below LF point	64	0.83	0.74	0.89	214	95	53	24
Maximum change in distance (m)	13	72.12	72.49	1.01	273	121	68	30

Table 3: Estimates of means, standard deviations, and coefficients of variation from *screened eastern WA data at terminal point types* with sample size approximations for four levels of relative precision.

Outcome	n	Est. Mean	SD	CV	$r =$ 0.10	$r =$ 0.15	$r =$ 0.20	$r =$ 0.30
Reach gradient (%) above LF point	126	20.25	14.64	0.72	141	63	35	16
Reach gradient (%) below LF point	108	11.30	4.81	0.43	49	22	12	5
Reach gradient difference (%)	108	5.87	8.92	1.52	624	277	156	69
Bankfull width (m) above LF point	123	2.57	1.52	0.59	95	42	24	11
Bankfull width (m) below LF point	110	2.43	1.28	0.53	75	34	19	8
Maximum change in distance (m)	108	73.40	195.84	2.67	1926	856	481	214

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Reach gradient difference (%)	161	9.96	11.19	1.12	341	152	85	38
Bankfull width (m) above LF point	197	2.14	1.41	0.66	117	52	29	13
Bankfull width (m) below LF point	174	1.84	1.35	0.74	146	65	37	16
Maximum change in distance (m)	121	73.26	186.34	2.54	1751	778	438	195

Table 2: Estimates of means, standard deviations, and coefficients of variation from *screened eastern WA data at lateral point types* with sample size approximations for four levels of relative precision.

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Reach gradient (%) above LF point	67	24.03	12.36	0.52	72	32	18	8
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Reach gradient (%) above LF point	126	20.25	14.64	0.72	141	63	35	16
Reach gradient (%) below LF point	108	11.30	4.81	0.43	49	22	12	5
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Bankfull width (m) above LF point	123	2.57	1.52	0.59	95	42	24	11
Bankfull width (m) below LF point	110	2.43	1.28	0.53	75	34	19	8
Maximum change in distance (m)	108	73.40	195.84	2.67	1926	856	481	214

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Table 2: Estimates of means, standard deviations, and coefficients of variation from *screened eastern WA data at lateral point types* with sample size approximations for four levels of relative precision.

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Table 4: Estimates of means, standard deviations, and coefficients of variation from *unscreened eastern WA data pooled across point types* with sample size approximations for four levels of relative precision (recommended eastern WA sample size in bold).

Outcome	n	Est. Mean	SD	CV	r = 0.10	r = 0.15	r = 0.20	r = 0.30
Reach gradient (%) above LF point	268	18.73	13.30	0.71	136	61	34	15
Reach gradient (%) below LF point	227	9.72	6.42	0.66	118	52	29	13
Reach gradient difference	227	8.13	10.23	1.26	428	190	107	48
Bankfull width (m) above LF point	282	2.02	1.47	0.73	143	63	36	16
Bankfull width (m)below LF point	264	1.59	1.30	0.81	179	79	45	20
Maximum change in distance (m)	153	74.21	172.56	2.33	1463	650	366	163

Table 5: Estimates of means, standard deviations, and coefficients of variation from *unscreened eastern WA data at lateral point types* with sample size approximations for four levels of relative precision.

Outcome	n	Est. Mean	SD	CV	r = 0.10	r = 0.15	r = 0.20	r = 0.30
Reach gradient (%) above LF point	104	19.65	12.76	0.65	114	51	29	13
Reach gradient (%) below LF point	83	7.90	8.22	1.04	293	130	73	33
Reach gradient difference (%)	83	13.65	10.92	0.80	173	77	43	19
Bankfull width (m) above LF point	129	1.38	0.81	0.59	93	41	23	10
Bankfull width (m) below LF point	116	0.72	0.71	0.98	261	116	65	29
Maximum change in distance (m)	14	67.89	71.42	1.05	299	133	75	33

Table 6: Estimates of means, standard deviations, and coefficients of variation from *unscreened eastern WA data at terminal point types* with sample size approximations for four levels of relative precision.

Outcome	n	Est. Mean	SD	CV	r = 0.10	r = 0.15	r = 0.20	r = 0.30
Reach gradient (%) above LF point	164	18.15	13.64	0.75	153	68	38	17
Reach gradient (%) below LF point	144	10.77	4.83	0.45	55	24	14	6
Reach gradient difference (%)	144	4.94	8.31	1.68	765	340	191	85
Bankfull width (m) above LF point	153	2.55	1.67	0.65	115	51	29	13
Bankfull width (m) below LF point	148	2.28	1.24	0.55	80	36	20	9
Maximum change in distance (m)	139	74.85	179.75	2.40	1561	694	390	173

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Table 4: Estimates of means, standard deviations, and coefficients of variation from *unscreened eastern WA data pooled across point types* with sample size approximations for four levels of relative precision (recommended eastern WA sample size in bold).

Outcome	n	Est. Mean	SD	CV	r = 0.10	r = 0.15	r = 0.20	r = 0.30
Reach gradient (%) above LF point	268	18.73	13.30	0.71	136	61	34	15
Reach gradient (%) below LF point	227	9.72	6.42	0.66	118	52	29	13
Reach gradient difference	227	8.13	10.23	1.26	428	190	107	48
Bankfull width (m) above LF point	282	2.02	1.47	0.73	143	63	36	16
Bankfull width (m)below LF point	264	1.59	1.30	0.81	179	79	45	20
Maximum change in distance (m)	153	74.21	172.56	2.33	1463	650	366	163

Table 5: Estimates of means, standard deviations, and coefficients of variation from *unscreened eastern WA data at lateral point types* with sample size approximations for four levels of relative precision.

Outcome	n	Est. Mean	SD	CV	r = 0.10	r = 0.15	r = 0.20	r = 0.30
Reach gradient (%) above LF point	104	19.65	12.76	0.65	114	51	29	13
Reach gradient (%) below LF point	83	7.90	8.22	1.04	293	130	73	33
Reach gradient difference (%)	83	13.65	10.92	0.80	173	77	43	19
Bankfull width (m) above LF point	129	1.38	0.81	0.59	93	41	23	10
Bankfull width (m) below LF point	116	0.72	0.71	0.98	261	116	65	29
Maximum change in distance (m)	14	67.89	71.42	1.05	299	133	75	33

Table 6: Estimates of means, standard deviations, and coefficients of variation from *unscreened eastern WA data at terminal point types* with sample size approximations for four levels of relative precision.

Outcome	n	Est. Mean	SD	CV	r = 0.10	r = 0.15	r = 0.20	r = 0.30
Reach gradient (%) above LF point	164	18.15	13.64	0.75	153	68	38	17
Reach gradient (%) below LF point	144	10.77	4.83	0.45	55	24	14	6
Reach gradient difference (%)	144	4.94	8.31	1.68	765	340	191	85
Bankfull width (m) above LF point	153	2.55	1.67	0.65	115	51	29	13
Bankfull width (m) below LF point	148	2.28	1.24	0.55	80	36	20	9
Maximum change in distance (m)	139	74.85	179.75	2.40	1561	694	390	173

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Table 7: Estimates of means, standard deviations, and coefficients of variation from *western Washington WTMF data pooled across point types* with sample size approximations for four levels of relative precision (recommended western WA sample size in bold).

Outcome	n	Est. Mean	SD	CV	r = 0.10	r = 0.15	r = 0.20	r = 0.30
Reach gradient (%) above LF point	1982	17.59	13.97	0.79	**171**	76	43	19
Reach gradient (%) below LF point	1512	5.96	4.13	0.69	130	58	32	14
Reach gradient difference (%)	1505	10.79	13.39	1.24	416	185	104	46
Bankfull width above LF point	1900	1.00	0.76	0.76	157	70	39	17
Bankfull width below LF point	1502	4.18	5.79	1.38	518	230	130	58

Table 8: Estimates of means, standard deviations, and coefficients of variation from *western Washington WTMF data at lateral point types* with sample size approximations for four levels of relative precision.

Outcome	n	Est. Mean	SD	CV	r = 0.10	r = 0.15	r = 0.20	r = 0.30
Reach gradient (%) above LF point	1393	19.65	15.45	0.79	167	74	42	19
Reach gradient (%) below LF point	921	4.23	2.81	0.66	119	53	30	13
Reach gradient difference (%)	916	15.13	14.86	0.98	261	116	65	29
Bankfull width (m) above LF point	1318	0.81	0.54	0.67	121	54	30	13
Bankfull width (m) below LF point	913	5.90	6.86	1.16	367	163	92	41

Table 9: Estimates of means, standard deviations, and coefficients of variation from *western Washington WTMF data at terminal point types* with sample size approximations for four levels of relative precision.

Outcome	n	Est. Mean	SD	CV	r = 0.10	r = 0.15	r = 0.20	r = 0.30
Reach gradient (%) above LF point	589	12.71	7.60	0.60	97	43	24	11
Reach gradient (%) below LF point	591	8.65	4.41	0.51	70	31	18	8
Reach gradient difference (%)	589	4.06	6.34	1.56	661	294	165	73
Bankfull width (m) above LF point	582	1.44	0.98	0.68	125	55	31	14
Bankfull width (m) below LF point	589	1.53	0.92	0.61	99	44	25	11

Initial results from the sample size approximation (Tables 1 through 9) suggested to the ISAG subgroup that upstream metrics provided a robust basis for sample size approximation. Upstream gradient and bankfull width metrics were consistently measured and are ecologically meaningful for both point types, were available for both eastern and western WA data, and were the most precise among the channel characteristics examined. Furthermore, the subgroup also decided to use the unscreened data for sample size approximations based on eastern WA data because the metrics were slightly more variable in this data set and provide more conservative sample sizes.

To obtain an overall statewide sample size that accounted for variation across the state, the unscreened eastern data and the western data were pooled. Coefficients of variation for estimates of means of both upstream metrics were computed to generate statewide sample sizes across both point types (Table 10),

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Table 7: Estimates of means, standard deviations, and coefficients of variation from *western Washington WTMF data pooled across point types* with sample size approximations for four levels of relative precision (recommended western WA sample size in bold).

Outcome	n	Est. Mean	SD	CV	r = 0.10	r = 0.15	r = 0.20	r = 0.30
Reach gradient (%) above LF point	1982	17.59	13.97	0.79	171	76	43	19
Reach gradient (%) below LF point	1512	5.96	4.13	0.69	130	58	32	14
Reach gradient difference (%)	1505	10.79	13.39	1.24	416	185	104	46
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Table 8: Estimates of means, standard deviations, and coefficients of variation from *western Washington WTMF data at lateral point types* with sample size approximations for four levels of relative precision.

Outcome	n	Est. Mean	SD	CV	r = 0.10	r = 0.15	r = 0.20	r = 0.30
Reach gradient (%) above LF point	1393	19.65	15.45	0.79	167	74	42	19
Reach gradient (%) below LF point	921	4.23	2.81	0.66	119	53	30	13
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Table 9: Estimates of means, standard deviations, and coefficients of variation from *western Washington WTMF data at terminal point types* with sample size approximations for four levels of relative precision.

Outcome	n	Est. Mean	SD	CV	r = 0.10	r = 0.15	r = 0.20	r = 0.30
Reach gradient (%) above LF point	589	12.71	7.60	0.60	97	43	24	11
Reach gradient (%) below LF point	591	8.65	4.41	0.51	70	31	18	8
Reach gradient difference (%)	589	4.06	6.34	1.56	661	294	165	73
Bankfull width (m) above LF point	582	1.44	0.98	0.68	125	55	31	14
Bankfull width (m) below LF point	589	1.53	0.92	0.61	99	44	25	11

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Table 7: Estimates of means, standard deviations, and coefficients of variation from *western Washington WTMF data pooled across point types* with sample size approximations for four levels of relative precision (recommended western WA sample size in bold).

Outcome	n	Est. Mean	SD	CV	r = 0.10	r = 0.15	r = 0.20	r = 0.30
Reach gradient (%) above LF point	1982	17.59	13.97	0.79	**171**	76	43	19
Reach gradient (%) below LF point	1512	5.96	4.13	0.69	130	58	32	14
Reach gradient difference (%)	1505	10.79	13.39	1.24	416	185	104	46
Bankfull width above LF point	1900	1.00	0.76	0.76	157	70	39	17
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Outcome	n	Est. Mean	SD	CV	r = 0.10	r = 0.15	r = 0.20	r = 0.30
Reach gradient (%) above LF point	1393	19.65	15.45	0.79	167	74	42	19
Reach gradient (%) below LF point	921	4.23	2.81	0.66	119	53	30	13
Reach gradient difference (%)	916	15.13	14.86	0.98	261	116	65	29
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Outcome	n	Est. Mean	SD	CV	r = 0.10	r = 0.15	r = 0.20	r = 0.30
Reach gradient (%) above LF point	589	12.71	7.60	0.60	97	43	24	11
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for lateral points (Table 11), and for terminal points (Table 12). From this analysis, a conservative statewide minimal sample size of surveyed sites to provide relative precision of 0.10 is obtained from the upstream bankfull width approximation of 190 sites (Table 10). Assuming that the proportion of sites classified as lateral points is similar to the proportion observed in the eastern WA data set (46%) and western WA data set (70%), we can expect roughly 87 to 133 lateral sites and 57 to 103 terminal sites from this sample of 190 sites. These sample sizes within each point type should be sufficient to obtain means of the two upstream metrics with at least 0.15 relative precision (Tables 11 and 12).

Table 10: Estimates of means, standard deviations, and coefficients of variation from *pooled eastern and western Washington data at all point types* with sample size approximations for four levels of relative precision.

Outcome	n	Est. Mean	SD	CV	r = 0.10	r = 0.15	r = 0.20	r = 0.30
Reach gradient (%) above LF point	2250	17.73	13.89	0.78	166	74	42	18
Bankfull width (m) above LF point	2182	1.13	0.95	0.84	190	84	47	21

Table 11: Estimates of means, standard deviations, and coefficients of variation from *pooled eastern and western Washington data at lateral point types* with sample size approximations for four levels of relative precision.

Outcome	n	Est. Mean	SD	CV	r = 0.10	r = 0.15	r = 0.20	r = 0.30
Reach gradient (%) above LF point	1497	19.65	15.28	0.78	164	73	41	18
Bankfull width (m) above LF point	1447	0.86	0.59	0.69	129	57	32	14

Table 12: Estimates of means, standard deviations, and coefficients of variation from *pooled eastern and western Washington data at terminal point types* with sample size approximations for four levels of relative precision.

Outcome	n	Est. Mean	SD	CV	r = 0.10	r = 0.15	r = 0.20	r = 0.30
Reach gradient (%) above LF point	753	13.90	9.52	0.69	127	56	32	14
Bankfull width (m) above LF point	735	1.67	1.24	0.74	149	66	37	17

This analysis provides guidance for establishing the sample size of sites for PHB surveys in eastern and western Washington. If the data sets that were provided are not representative of the larger population of PHBs in Washington, then variation may be underestimated causing approximated sample sizes to be lower than needed for the desired precision. The unscreened CMER data were used for the sample size approximation because they provided more conservative sample sizes than when the screened data were used. However, this application does not imply a preference for the unscreened data set relative to other analyses. Differences in site selection for eastern and western Washington data sets were not considered when pooling the data, but the combined data set provided an index of statewide variability that was not available otherwise. While the ultimate goal of this project is to identify criteria with which to identify

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Table 10: Estimates of means, standard deviations, and coefficients of variation from *pooled eastern and western Washington data at all point types* with sample size approximations for four levels of relative precision.

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Table 12: Estimates of means, standard deviations, and coefficients of variation from *pooled eastern and western Washington data at terminal point types* with sample size approximations for four levels of relative precision.

Outcome	n	Est. Mean	SD	CV	*r* = 0.10	*r* = 0.15	*r* = 0.20	*r* = 0.30
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PHBs, ensuring that the data collected on potential PHB criteria represent the range of conditions in the population will provide a robust basis for PHB modeling when three years of data are available.

Sampling Design Recommendations

Probabilistic selection of the sampling locations from the sampling frame is recommended to avoid selection bias and to provide a basis for inference to the larger population of interest (Lohr 2009). For ecological surveys, spatially-balanced sampling approaches provide methods to obtain probabilistic samples across large areas without risking selection of clustered points that are correlated and provide duplicate information. Several methods for selecting spatially-balanced samples are available and include generalized random tessellation stratified (GRTS) sampling (Stevens and Olsen 2003, 2004), balanced acceptance sampling (BAS; Robertson et al. 2013), and Halton iterative partitioning (HIP, Robertson et al. 2018). Data from samples selected with spatially-balanced sampling can be analyzed with design-based tools available in the *spsurvey* package (Kincaid et al. 2019). All three of the sampling techniques can be implemented in the *SDraw* package (McDonald and McDonald 2020). However, since the *SDraw* package is currently not maintained on the CRAN website (as of 12/6/21 and since 11/16/21), drawing GRTS samples with the *spsurvey* package is recommended.

The sampling design for the PHB surveys will incorporate *a priori* geographic stratification by region (east or west WA) so that spatial balance is obtained for each region. Additionally, sampling effort will be apportioned among point types (terminal or lateral points) with "soft stratification." In this approach, the point types are not available for each site before the survey so no sampling frame is available to identify each subpopulation for a priori stratification. Survey crews will record the point type at the time of the survey and, when the desired sample size for a point type is satisfied, survey data from this point type will not be collected at subsequent points of this type. Because soft stratification cannot be planned in advance, employing this technique will require some adherence to the spatially-balanced ordered list of sites to ensure that the obtained sample of sites within each point type is also spatially balanced. The point type should be recorded for each site so that inclusion probabilities for each site may be calculated prior to analysis for any design-based summaries such as means and totals.

Based on the sample size approximation for data pooled across region, the total sample size should be no less than 190 sites (Table 10) to obtain relation precision of 0.10 for the statewide estimates of mean channel characteristics. ISAG members expressed a desire to obtain estimates of means for channel characteristics with geographic stratum-level relative precision of 0.10. For the two metrics of interest (reach gradient above LF point and bankfull width above LF point), obtaining the more conservative sample size for each region is recommended. Therefore, the eastern WA sample should consist of 143 sites (Table 4) and the western WA sample should consist of 171 sites (Table 7) for a total of 314 sites across the state.

Given the ISAG statement that there are roughly five times more lateral points than terminal points, I examined methods to allocate sampling effort among the two point types. Proportional allocation of effort will favor lateral points since they exist more frequently throughout the landscape. Optimal allocation accounts for the relative precision of lateral and terminal points but is still influenced by the larger

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The sampling design for the PHB surveys will incorporate *a priori* geographic stratification by region (east or west WA) so that spatial balance is obtained for each region. Additionally, sampling effort will be apportioned among point types (terminal or lateral points) with "soft stratification." In this approach, the point types are not available for each site before the survey so no sampling frame is available to identify each subpopulation for a priori stratification. Survey crews will record the point type at the time of the survey and, when the desired sample size for a point type is satisfied, survey data from this point type will not be collected at subsequent points of this type. Because soft stratification cannot be planned in advance, employing this technique will require some adherence to the spatially-balanced ordered list of sites to ensure that the obtained sample of sites within each point type is also spatially balanced. The point type should be recorded for each site so that inclusion probabilities for each site may be calculated prior to analysis for any design-based summaries such as means and totals.

Based on the sample size approximation for data pooled across region, the total sample size should be no less than 190 sites (Table 10) to obtain relation precision of 0.10 for the statewide estimates of mean channel characteristics. ISAG members expressed a desire to obtain estimates of means for channel characteristics with geographic stratum-level relative precision of 0.10. For the two metrics of interest (reach gradient above LF point and bankfull width above LF point), obtaining the more conservative sample size for each region is recommended. Therefore, the eastern WA sample should consist of 143 sites (Table 4) and the western WA sample should consist of 171 sites (Table 7) for a total of 314 sites across the state.

Given the ISAG statement that there are roughly five times more lateral points than terminal points, I examined methods to allocate sampling effort among the two point types. Proportional allocation of effort will favor lateral points since they exist more frequently throughout the landscape. Optimal allocation accounts for the relative precision of lateral and terminal points but is still influenced by the larger

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relative frequency of lateral points as compared to terminal points. The final sample sizes were based on reach gradient above LF point in eastern WA and bankfull width above LF point in eastern WA. The precision in the means for these two sets of estimates were similar between lateral and terminal point types. Therefore, I recommend an equal allocation of sampling effort among the two point types. Based on the sample size approximation of lateral and terminal points for eastern and western WA (Tables 5, 6, 8, and 9), equal allocation of effort between the two point types should still provide channel characteristic means with relative precision between 0.10 and 0.15.

Note that the suggested sample sizes are the numbers of sites where data are successfully collected. To account for inaccessible sites and sites that do not meet the definition of the target population (such as in reaches with no water), a larger sample of sites (perhaps three to five times larger than the desired sample size) should be drawn to successfully collect data at the desired number of sites. There is no penalty for selecting a much larger sample than needed, but the final set of surveyed sites should consist of a contiguous set of sites from the spatially-balanced randomized list of locations to avoid any sort of systematic or geographic bias in the sample locations caused by surveying a disproportionate number of sites in one area. For each site visited, notes on any frame error or nonresponse error should be recorded so that inclusion probabilities for each site can be accurately calculated. For model-based analysis approaches, incorporating design variables such as *a priori* and soft stratification variables such as region and point type (lateral or terminal) may account for the sampling design without directly incorporating inclusion probabilities.

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PH

Appendix C. Random Forest Modeling Report

Identifying Potential Habitat Breaks in Washington Streams Using Random Forest Modeling

Prepared for:

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July 21, 2022

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OBJECTIVES

The Washington Department of Natural Resources (WA DNR) is developing a survey protocol to identify physical characteristics associated with fish habitat breaks in Washington streams. In addition to developing criteria for identifying potential habitat breaks (PHBs), the Instream Scientific Advisory Group (ISAG) would like to evaluate criteria proposed by the Washington Forest Practices Board (FPB or Board). The goal of this analysis is to characterize the features associated with the end of fish occurrence in each stream. The goals of this pilot data analysis are to demonstrate methods for identifying PHBs and assessing FPB criteria. ISAG provided pilot data from streams in eastern and western Washington to facilitate an example analysis to identify the end of fish in each stream.

This pilot data analysis demonstrates several tools available for characterizing the end of fish. A random forest analysis (Cutler et al. 2007) was applied to segment-level stream data to model fish presence as a function of habitat feature metrics. Random forest modeling generates a predictive model that can be accurately applied to novel datasets. Additionally, interaction forest models were applied to accommodate multivariate comparisons of habitat covariates that may exhibit relatively strong interactions. Random forest models were developed with R statistical software (2022) packages to evaluate the Board criteria that included binary categorical variables of stream characteristics, including gradient, width, obstacles, and other physical stream characteristics that affect or limit fish dispersal further upstream. For this objective, we trained a separate random forest model for each of three FPB-proposed PHB groups identifying criteria options for PHBs based on barrier, gradient, and width criteria, and a model for all seven unique criteria combined.

Random forest methodology does not explicitly identify the location of the end of fish, but stream metrics that are cumulative over multiple segments above or below a given segment can be used to explain habitat relationships with fish distribution at a broader scale rather than only at the segment scale. Additional techniques that could be used to identify the end of fish using the habitat metrics identified by the random forest analysis are addressed in the discussion.

METHODS

Pilot Data and Covariates

The pilot data set used for analysis included measurements from 2,313 stream segments representing 32 stream reaches across 11 basins, spanning western and eastern Washington and five ecoregions (Eastern: Canadian Rocky Mountains, East Cascades; Western: Northwest Coast Ecoregion [under the purview of WA DNR], Puget Trough, and West Cascades). Stream segments are defined as the stretch of stream between two survey stations, which are located at inflection points in the topography of the stream thalweg (Roni et al. 2018). Segment-level habitat metrics were provided for the random forest analysis. To expand the scale of habitat metrics for the predictive models, several covariates used in the analysis aggregate data from continuous groups of segments either upstream or downstream of the segment of interest. Examples include the maximum gradient upstream of a particular segment and the average sustained gradient of the 20 segments upstream from the segment of interest. We assessed the correlation between variables to eliminate covariate combinations that were highly correlated and redundant (Table 1) to avoid bias in variance importance metrics (Strobl et al. 2007, 2008), but retained all variables when not included in the same model.

Table 1. Details of which stream characteristics were correlated (>0.6). All characteristics were retained in this demonstration analysis to help determine which variables may be important for data collection.

Variable 1	Variable 2	Correlation
Eff.Step.Ht.m	Eff.Step.Ht.BFW	0.88
Eff.Grad	DelEff.Grad.Dn	0.72
Avg.Sus.Grad.Up	Del.Sus.Grad.UpDn	0.70
Avg.Sus.Grad.Dn	Max.Dn.Grad	0.65
Max.Dn.Grad	Max.Dn.Step.BFW10	0.63
Max.Up.Grad	Max.Up.Step.BFW10	0.63

Avg= average; BFW = bankfull width; BFW10 = ?; DelEff = change in effective; Dn = downstream; Eff = effective; Grad = gradient; Ht = height; m = meter; Step = Segment step:Sus = sustained; Up = upstream

Random Forest Models

Random forest classification models can predict binary outcomes such as stream segments with fish or without fish, can accommodate both continuous and categorical (including binary) covariates, and are useful in identifying important covariates from covariates sets with substantial interactions (Cutler et al. 2007). Random forest does not explicitly identify the end of fish based on habitat characteristics, but provides a method for identifying variables that describe the binary state of a stream segment that does or does not contain fish.

Using a random forest model requires training and testing (validation) before applying the model to novel data sets. We trained a number of models and evaluated model performance to provide accurate prediction at different spatial scales. In this process, we used the full data set across Washington and split the data into east and west subsets to determine how transferrable the model might be across the entire state. For the first approach, we trained the model on a random subset of 80% of all stream segments across the Washington State dataset. The remaining segments were used for validation. This statewide *Full Random* model was compared to a model that was trained on all streams but one, which is referred to as *Full Random Leave One Out (LOO)* approach. The segments from the "left out" stream were used for model validation. We also compared the *Full Random* model performance to a model that incorporated geographic west/east as a predictor variable (*Full Random WE Predictor*). We performed the same routine for both the western (*Western Random and Western Random* LOO) and eastern (*Eastern Random* and *Eastern Random LOO*) regions in Washington. All models initially included categorical variables for substrate and unit type.

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Random forest models cannot accommodate missing values in covariates. The *randomForest* package (Liaw and Wiener 2002) can impute these values based on the mean of other correlated covariates; however, this is not appropriate for this data set. Values were missing for the upstream gradient of the last segment along the stream and for step-related covariates where no step was observed. In order to include the last segment of each stream, the gradient was set to zero. This corresponded to the trajectory of most streams, and several segments had several zero values prior to the last segment. Missing values for step-related covariates were also set to zero following the logic that a stream missing a step has a step height of zero. The *Full Random* model includes these covariates, whereas the *Full Random Reduced Covariates* model excludes the variables with missing values. This comparison may help in determining the suite of variables important for future data collection. All eastern and western models included the same covariates as the *Full Random* model because the *Full Random* model performed better than the *Full Random Reduced Covariates* model (Table 2).

Table 2. Tuning parameters obtained from package *caret*. Model performance evaluated with validation testing.

	mtry	Maxnodes	Number of Trees	AUC	Accuracy (PCC)	Sensitivity	Specificity	Kappa
Full Random Reduced Covariates	10	26	250	0.87	85.53%	0.92	0.82	0.69
Full Random	11	29	250	0.93	93.52%	0.91	0.96	0.87
Full Random (WE Predictor)	7	29	350	0.90	89.41%	0.91	0.88	0.78
Full Random (LOO)	12	24	250	0.86	82.14%	0.73	1.00	0.65
Eastern Random	6	24	250	0.93	92.83%	0.91	0.94	0.86
Eastern Random (LOO)	12	25	250	0.69	61.19%	0.8	0.58	0.20
Western Random	11	15	250	0.93	92.92%	0.91	0.94	0.85
Western Random (LOO)	5	19	250	0.86	86.08%	0.73	1.00	0.72

AUC = area under the curve; kappa = a measure of agreement between predicted presences and absences; LOO = Leave One Out; Maxnodes = maximum number of nodes; mtry = optimum number of covariates; PCC = proportion of presence correctly classified; sensitivity = proportion of presence correctly classified; specificity = the proportion of absence correctly classified

Each model was built and tuned to maximize accuracy using the R package *caret* (Kuhn 2008) and trained and validated using *randomForest* (Liaw and Wiener 2002). We determined the optimum number of covariates allowed at each node (*mtry*), the number of trees, and the maximum number of nodes (*max nodes*) by comparing the accuracy of the model with varying values of *mtry, number of trees,* and *max nodes*. Parameters were tuned for each data subset described in the previous section.

For final model evaluation and comparison, we reported the area under the curve (AUC) to compare model performance, accuracy (overall percentage correctly classified), sensitivity (proportion of presence correctly classified), specificity (the proportion of absence correctly classified), and kappa (a measure of agreement between predicted presences and absences). Variables deemed important by random forest are displayed graphically along with partial dependency plots for all continuous variables. To further validate the variables deemed important in *randomForest*, we used the package *Boruta* as a secondary way to characterize important variables for each model (Kursa and Rudnicki 2010). To increase the utility of this demonstration, an appendix of box plots and violin plots were produced to qualitatively visualize potential criteria cutoffs for variables deemed important by random forest analyses (see Appendix A).

Interaction Forest Models

The random forest approach described above does not explicitly account for interactions between covariates that can influence categorical outcomes (Hornung and Boulesteix 2022). To investigate how interactions between stream features effect the predictive capacity of the model, we fit an interaction forest model using the *Full Random* training data set. We used the R package *diversityForest* (Hornung 2022) to train an interaction forest and R package *iml* (Molnar et al. 2018) to visualize interactions between covariates. The package *diversityForest* uses bivariate splitting to model quantitative and qualitative interaction effects. The effect importance measure (EIM) is produced to rank variable pairs with respect to their predictive importance. The pairs with the highest EIM are displayed through contour plots and cross section plots based on a 2-dimensional LOESS fit. Additionally, graphical output for the overall strength of interactions for all pairs was produced using the *iml* package in R. Overall interaction strength is calculated using Friedman's H-statistic (Friedman and Popescu 2008). The H-statistic quantifies the share of variance that is explained by the interaction and represents the strength, but not the direction, of the interaction.

Evaluating Forest Practice Board proposed Potential Habitat Break Criteria

To evaluate the FPB-proposed PHB criteria for end of fish habitat designation (Table 3), we used the pilot data to compare observed fish presence to predicted fish presence for four sets of criteria. The FPB criteria options A, B, and C consist of seven unique criteria overall. Each of the seven unique criteria was calculated from the pilot data as a binary indicator that the criterion was met. The FPB criteria options A, B, and C were based on the specific combinations of test criteria within each Fish Habitat Assessment Methodology (FHAM) Rule Option as outlined in Table 3. Additionally, a fourth criteria set that included all seven unique test criteria was examined. Each of the four criteria sets was used to predict fish presence and the results were compared to the observed fish data. A confusion matrix of results, AUC, accuracy, sensitivity, and specificity are reported for each of the criteria sets. See Appendix B for covariate definitions used in the assessment of FPB criteria.

Table 3. List of draft Fish Habitat Assessment Methodology rule criteria (presented Washington Department of Natural Resources 2019) translated to metrics/variable names used for pilot analysis. The Forest Practices Board (FPB) Manual definition of bankfull width (BFW) as that for 10 times average BFW is used throughout unless specified otherwise. See Appendix B for variable definitions.

FHAM PHB Option	FHAM Draft Rule Line#	Criterion Type	FHAM Criterion Description	Criterion Description Translated to Pilot Data Variables	Test Criterion #
A	3-a-i	Gradient	Sustained gradient increase >= 5%; sustained = over 20*BFW	(AvgSusGradUpstrm-AvgSusGradDnstrm) >= 0.05	1
A	3-a-ii	Width	Bankfull width <= 2 feet (ft), sustained over 20*BFW	BFW_Up20_ft <= 2.0	2
A	3-a-iii-A	Obstacle	Vertical obstacle height >= BFW AND >= 3 ft	EffectiveGrad_pct > 150% AND EffectiveStepHeight_m >= (3*.3048) AND EffectiveStepHeight_BFW >=1.0	3
A	3-a-iii-B	Obstacle	Non-vertical step >= 30% AND elevation increase > 2*BFW	EffectiveGrad_pct >= 0.3 AND EffectiveStepHeight_BFW > 2.0	4
B	3-a	Gradient	Gradient >10%, sustained over 20 * BFW	AvgSusGradUpstrm > 10%	5
B	3-b (same as A 3-a-ii)	Width	Bankfull width <= 2 ft, sustained over 20*BFW	*See above*	
B	3-c-i (same as A 3-a-iii-A)	Obstacle	Vertical obstacle height >= BFW AND >= 3 ft	*See above*	
B	3-c-ii	Obstacle	Non-vertical step >= 20% gradient AND elevation increase >= upstream BFW	EffectiveGrad_pct >= 0.2 AND EffectiveStepHeight_m > BFW_Up10_m	6
C	3-i (same as A 3-a-i)	Gradient	Sustained gradient increase >= 5%; sustained for >= 20 * BFW	*See above*	
C	3-ii	Width	[Downstream to Upstream] BFW decrease >20%, sustained over 20 * BFW (at tributary junctions)	(BFW_Up20_m/BFW_Dn10_m) < 0.8	7

Table 3. List of draft Fish Habitat Assessment Methodology rule criteria (presented Washington Department of Natural Resources 2019) translated to metrics/variable names used for pilot analysis. The Forest Practices Board (FPB) Manual definition of bankfull width (BFW) as that for 10 times average BFW is used throughout unless specified otherwise. See Appendix B for variable definitions.

FHAM PHB Option	FHAM Draft Rule Line#	Criterion Type	FHAM Criterion Description	Criterion Description Translated to Pilot Data Variables	Test Criterion #
C	3-iii-A (same as A 3-a-iii-A)	Obstacle	Vertical obstacle height >= BFW AND > 3 feet	*See above*	
C	3-iii-B (same as B 3-c-ii)	Obstacle	Non-vertical step >= 20% gradient, and elevation increase >= upstream BFW	*See above*	
A, B, C		Tributary Jctn	Tributary junctions must meet one of the other PHB criteria	*none*	

*(4) For purposes of this section:

(a) "Permanent Natural Obstacle" means a natural, non-deformable obstacle that completely blocks upstream fish movement. "Permanent natural obstacles" include vertical drops, steep cascades, bedrock sheets and bedrock chutes. A permanent natural obstacle excludes large woody debris and sedimentary deposits.

(b) "Potential Habitat Break" means a permanent, distinct and measurable change to in-stream physical characteristics. PHBs are typically associated with underlying geomorphic conditions and may consist of natural obstacles that physically prevent fish access to upstream reaches or a distinct measurable change in channel, bankfull width or a combination of the two.

BFW = bankfull width; FHAM = Fish Habitat Assessment Methodology; Jctn = junction; PHB = Potential Habitat Break; pct = Percent; Upstrm = Upstream.

As a more robust comparison, we trained and tested four separate random forest models using the *Full Random* training approach and validation datasets described above and in Table 3. For each of the four criteria sets the original dataset was altered to contain the fish/no-fish classification column and a binary feature column; one column for each of the criteria within each set as outlined in Table 3. The *Boruta* package was used to validate variable importance. The model AUC, accuracy, sensitivity, specificity, and kappa are reported to evaluate model performance.

RESULTS

Random Forest Models

Of the eight random forest models, the full random model was most accurate (Table 2). The *Full Random* model including step covariates exhibited an accuracy of 93.52%, whereas the *Full Random* model without step covariates demonstrated 85.53% accuracy. The random sampling of stream segments as opposed to the leave one-out approach of an entire stream performed better for all data set groupings. The difference between the accuracy of the *Western Random*, (92.92%), and the *Western Random LOO*, (86.08%) was 6.84%. The difference in accuracy between *Full Random,* (93.52%) and the *Full Random LOO* (82.14%), was 11.38%. However, the greatest difference in accuracy, 31.64%, occurred between the *Eastern Random* (92.83%), and the *Eastern Random LOO* (61.19%). The *Full Random WE Predictor* model exhibited an accuracy of 89.41%, which was higher than the *Full Random LOO* accuracy of 82.14% but lower than the *Full Random* (93.52%). Tuning parameters between model iterations appears to be an important procedure for these data as the *mtry*, *max nodes*, and *number of trees* values differed across models at the same spatial scale and across spatial scales (Table 2).

Across almost all model iterations, the maximum upstream gradient (Max.Up.Grad) and maximum downstream gradient (Max.Dn.Grad) exhibited the top two highest variable importance scores (Figure 1). However, the maximum upstream step bankfull width (Max.Up.Step.BFW10) was the most important variable for the *Western Random* model. Gradient and step-related characteristics exhibited the highest variable importance scores across all models. Substrate and UnitLabel exhibited small importance scores for all models. Violin plots and box plots in Appendix A provide a qualitative assessment for possible test criteria to define end of fish for several of these important variables. For example, the average values for maximum downstream gradient for fish segments is lower than the average at the end of fish segment and the segment just above the end of fish. The analysis using the *Boruta* package concluded that almost all variables were deemed important for each model iteration (Figure 2), and importance values followed a similar pattern as that reported by the *randomForest* output (Figure 2). Unit type (UnitLabel) for *Western Random LOO* was deemed tentatively important and unimportant for the *Western Random* model (Figure 2d). Effective step height in meters (Eff.StepHt.m) and effective step height at bankfull width (Eff.StepHt.BFW) for the *Eastern Random* models were deemed tentatively important (Figure 2c). The partial dependency plots (Figure 3) demonstrate the importance of maximum downstream gradient, maximum upstream gradient, and bankfull width at predicting fish presence at a segment.

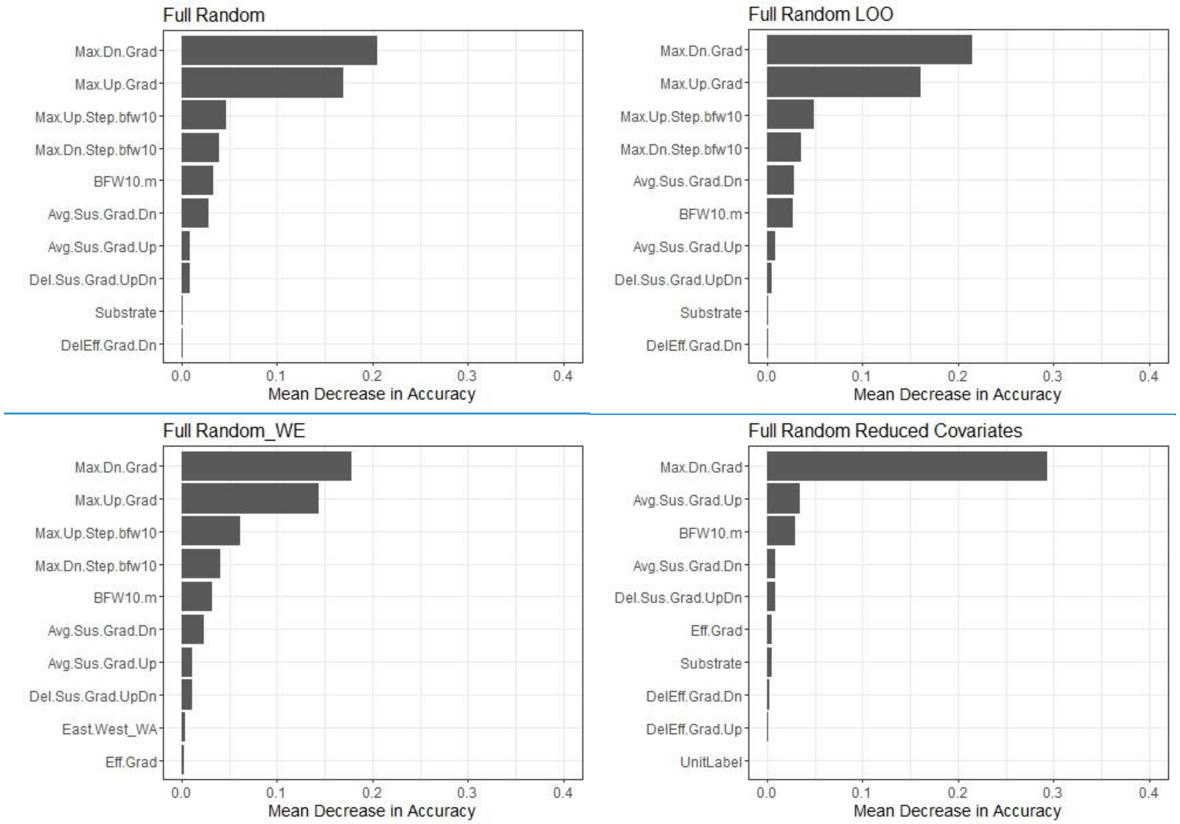
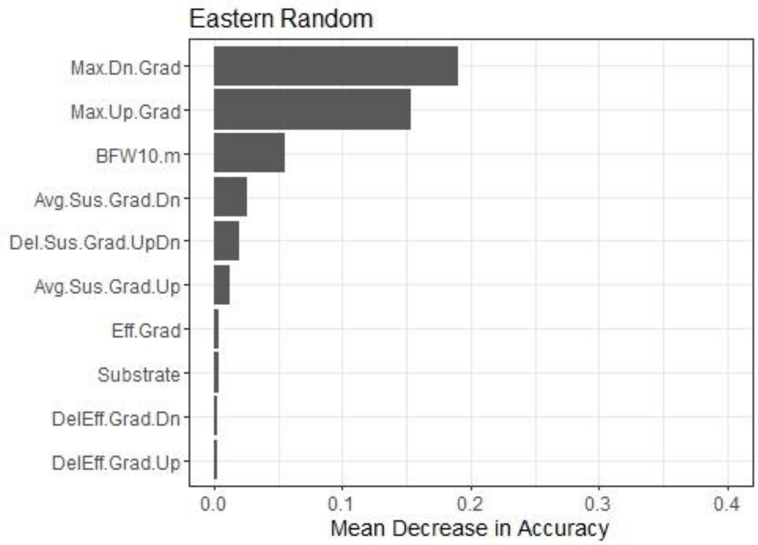


Figure 1a. Variable importance from random forest models using the *Full Random, Full Random Leave One Out (LOO), Full Random West/East (WE),* and *Full Random Reduced Covariates* data sets. Visualized using package vip (Greenwell and Boehmke 2020).



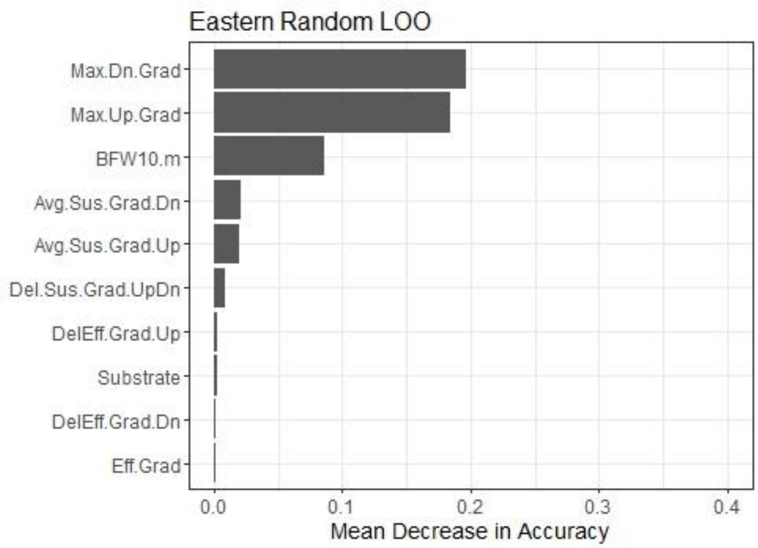
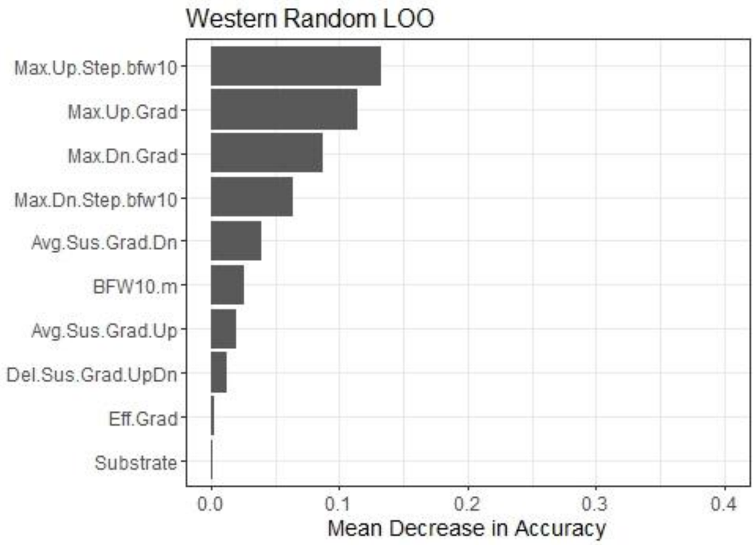


Figure 1b. Variable importance from random forest models using the *Eastern Random* and *Eastern Random Leave One Out (LOO)* data sets. Visualized using package vip (Greenwell and Boehmke 2020).



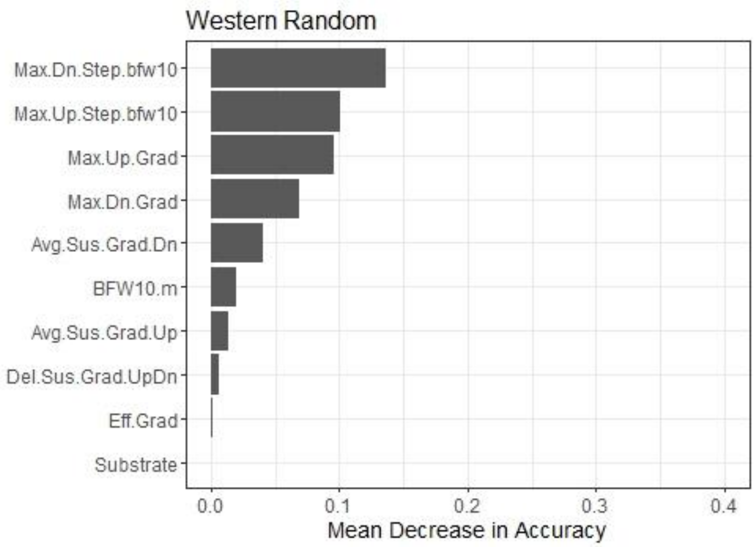


Figure 1c. Variable importance from random forest models using the *Western Random* and *Western Random Leave One Out (LOO)* data sets. Visualized using package vip (Greenwell and Boehmke 2020).

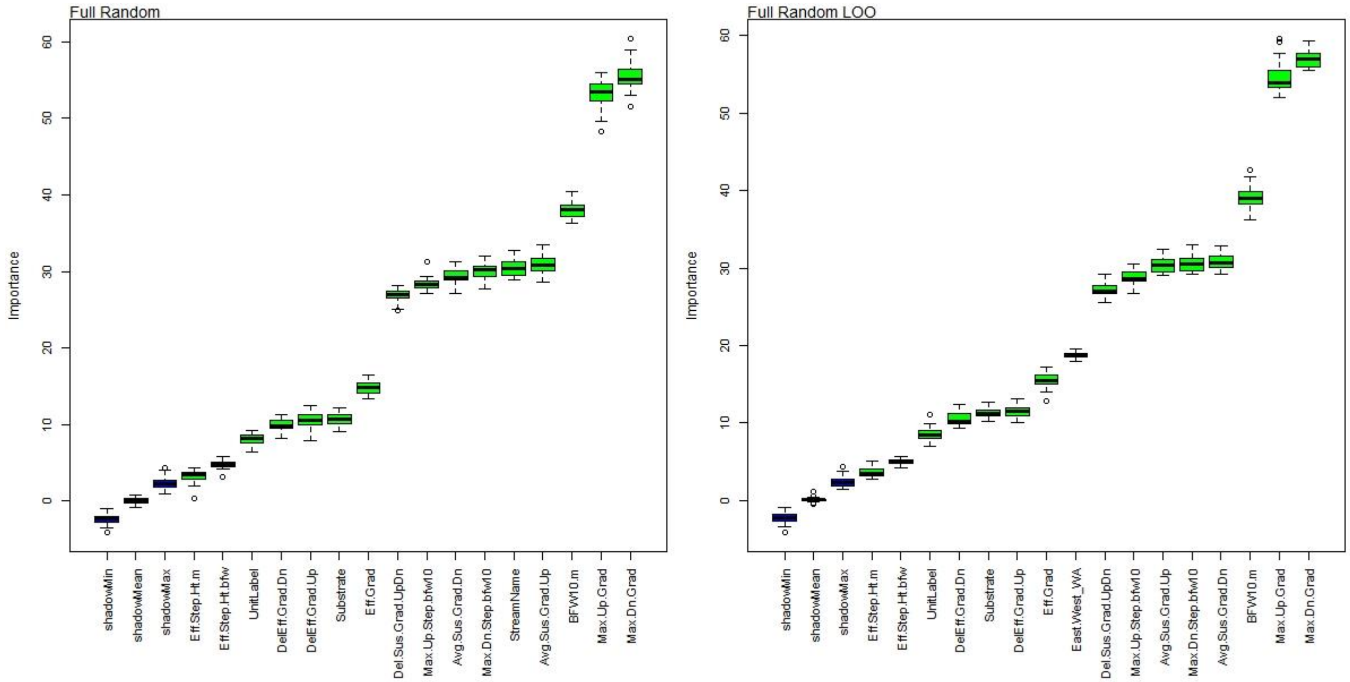


Figure 2a. **Confirming variable importance with *Boruta* package using the *Full Random* and the *Full Random Leave One Out* data sets. Features in green were deemed important by *Boruta,* yellow are tentatively important, red are unimportant, and blue are called shadow features from *Boruta.* Shadow features are shuffled copies of all features to add randomness to the *Boruta* algorithm.**

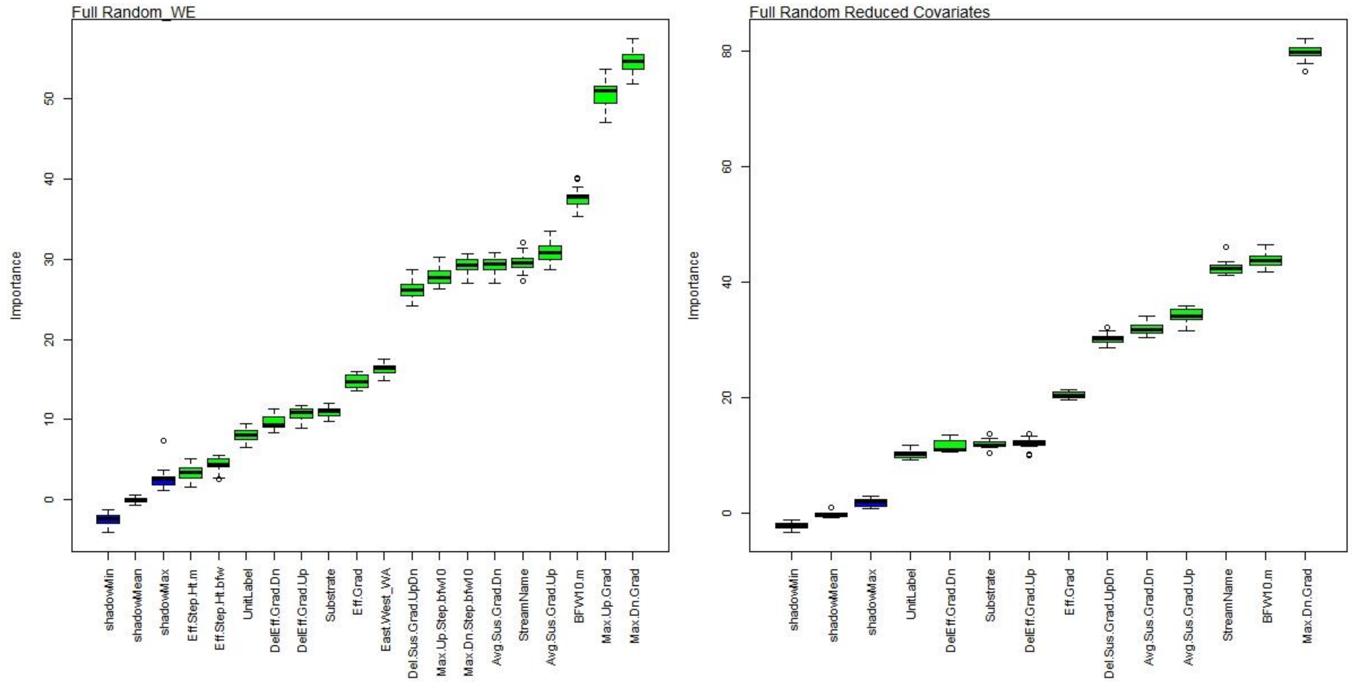


Figure 2b. Confirming variable importance with *Boruta* package using the *Full Random West/East (WE)*, and the *Full Random Reduced Covariates* data sets. Features in green were deemed important by *Boruta*, yellow are tentatively important, red are unimportant, and blue are called shadow features from *Boruta.* Shadow features are shuffled copies of all features to add randomness to the *Boruta* algorithm.

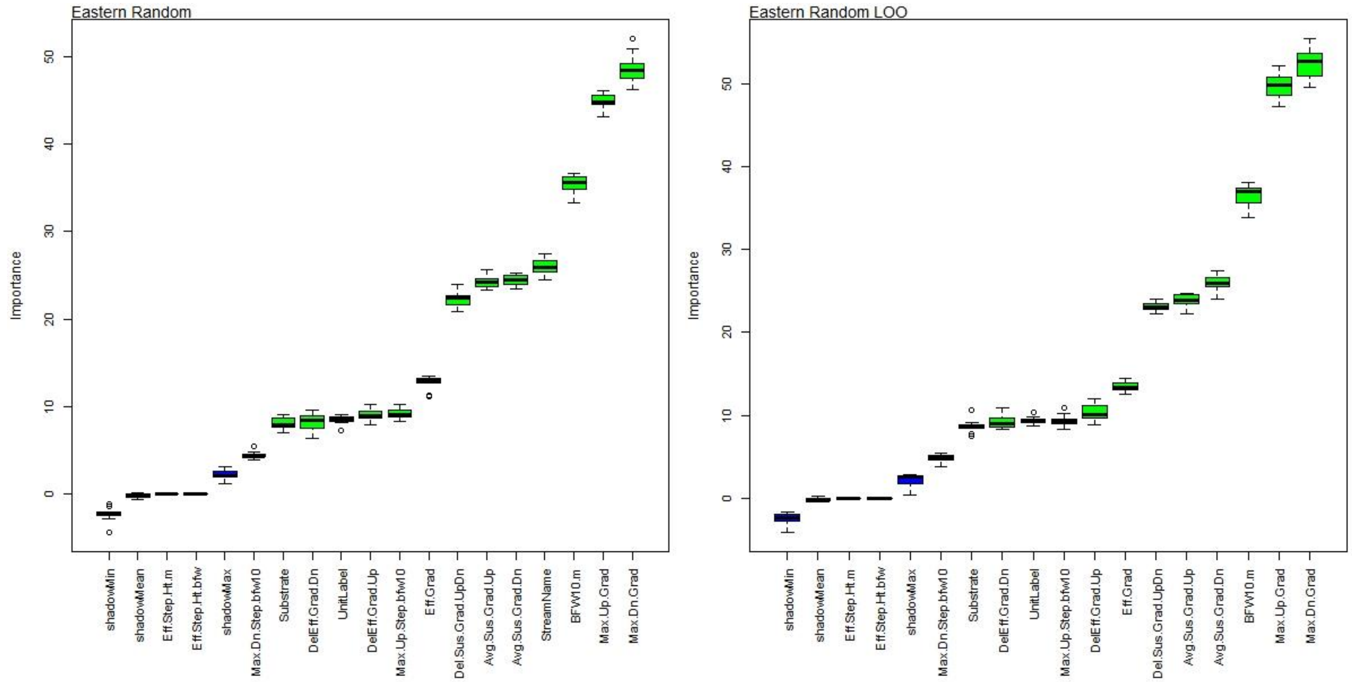


Figure 2c. **Confirming variable importance with *Boruta* package using the *Eastern Random* and *Eastern Random Leave One Out* data sets. Features in green were deemed important by *Boruta,* yellow are tentatively important, red are unimportant, and blue are called shadow features from *Boruta.* Shadow features are shuffled copies of all features to add randomness to the *Boruta* algorithm.**

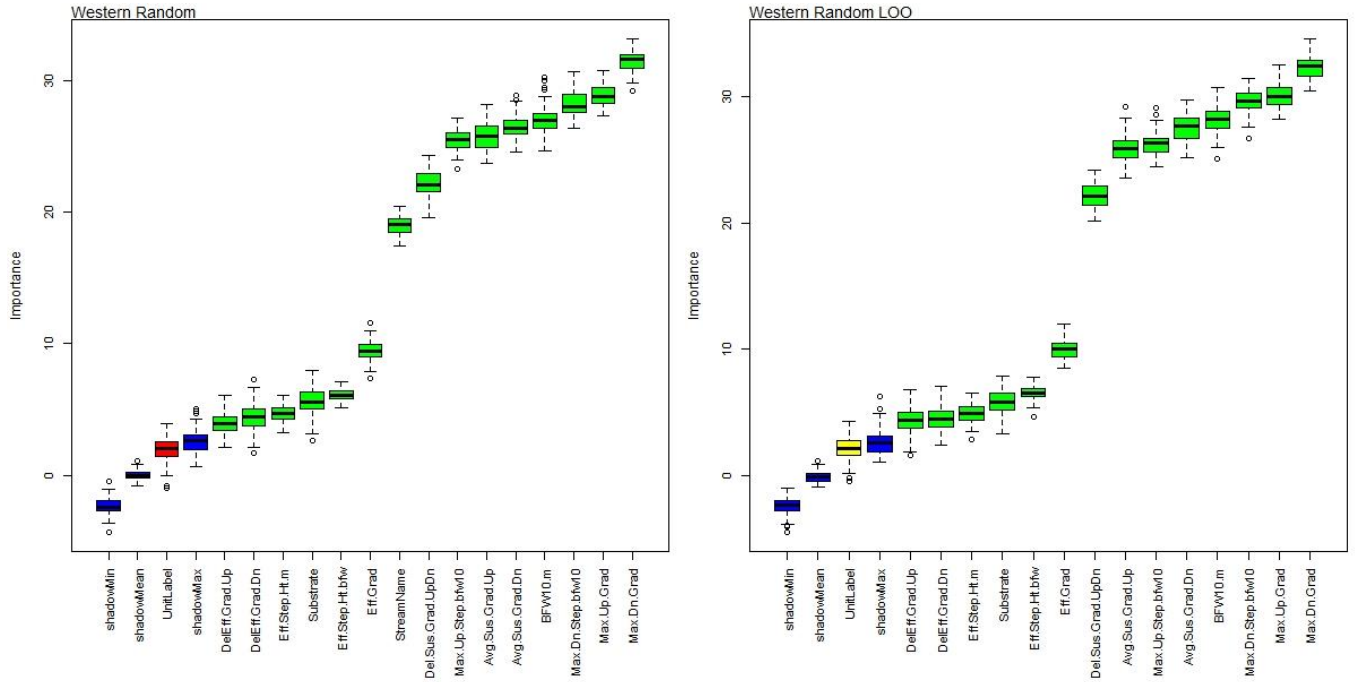


Figure 2d. Confirming variable importance with *Boruta* package using the *Western Random* and *Western Random Leave One Out* data sets. Features in green were deemed important by *Boruta*, yellow are tentatively important, red are unimportant, and blue are called shadow features from *Boruta*. Shadow features are shuffled copies of all features to add randomness to the *Boruta* algorithm.

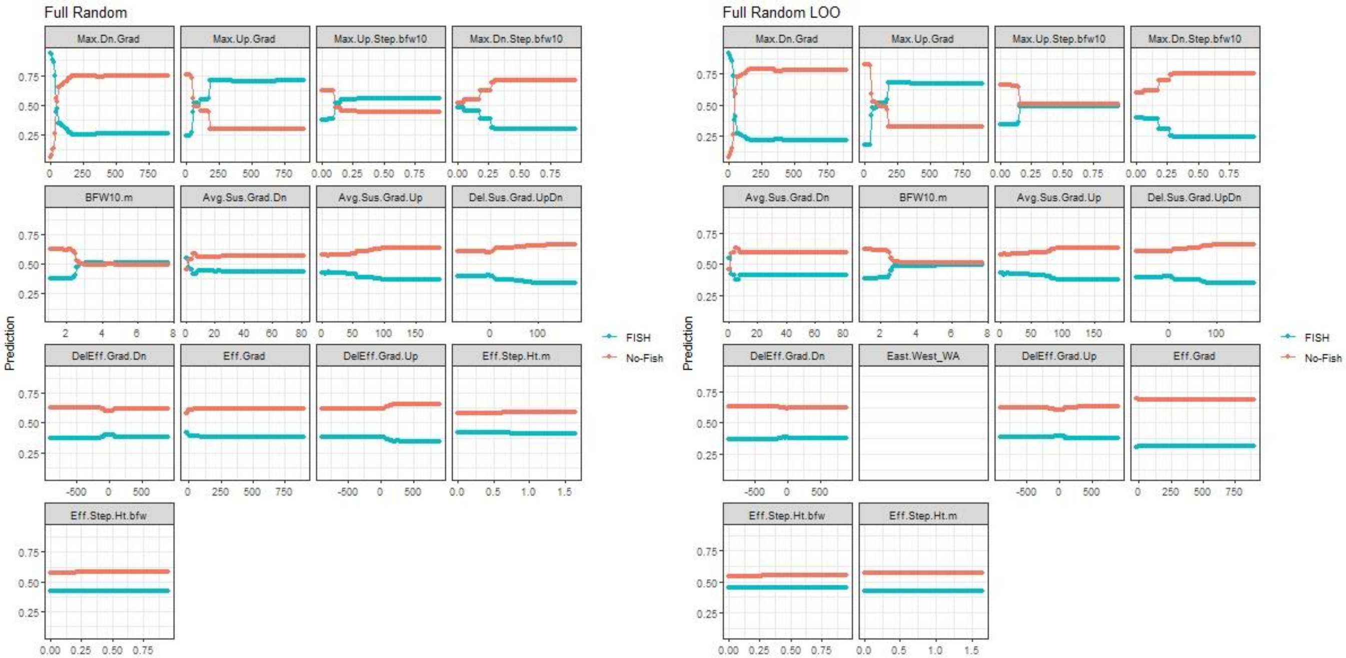


Figure 3a. Partial dependency plots in order of importance to the random forest model for *Full Random* and *Full Random Leave One Out (LOO)*. The y-axis represents the probability of prediction into a particular class based on the values for that particular feature. Substrate and unit are not displayed. *Full Random West/East Predictor* model output is not displayed because it follows the same pattern as the *Full Random* model.

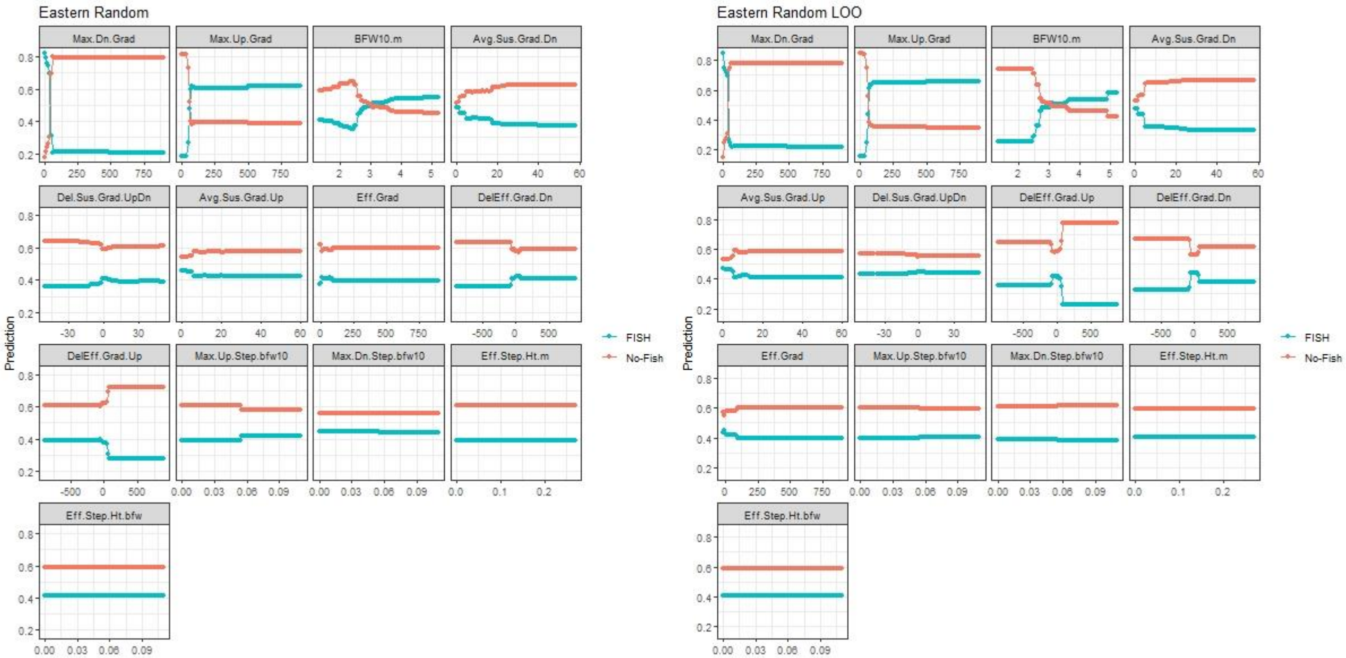


Figure 3b. Partial dependency plots in order of importance to the random forest model for *Eastern Random* and *Eastern Random Leave One Out (LOO)*. The y-axis represents the probability of prediction into a particular class based on the values for that particular feature. Substrate and unit are not displayed.

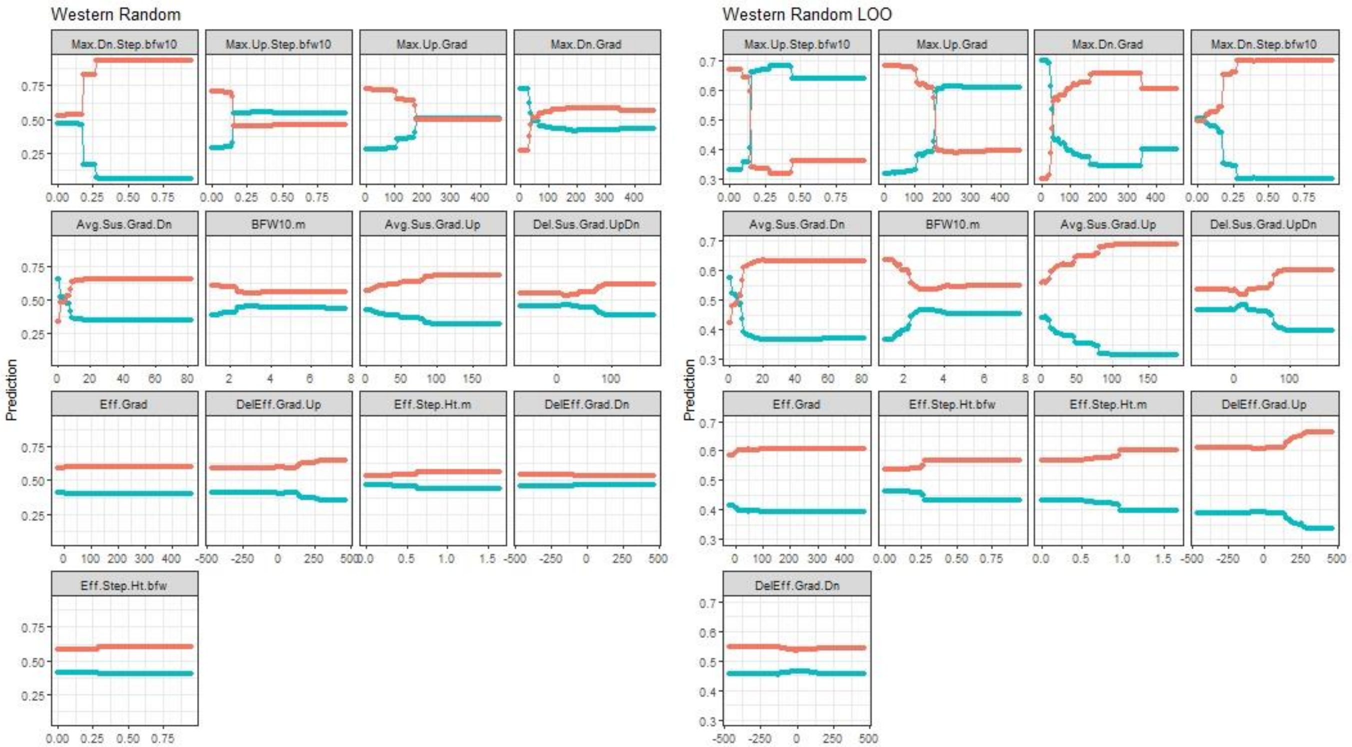


Figure 3c. **Partial dependency plots in order of importance to the random forest model for *Western Random* and *Western Random Leave One Out (LOO)*. The y-axis represents the probability of prediction into a particular class based on the values for that particular feature. Substrate and unit are not displayed.**

Interaction Forest Models

Using the pilot dataset, the interaction forest model produced a more accurate prediction (97.17%) than the random forest model, (89.63%; Table 4). The pairwise interaction strength for the five covariate pairs with the highest EIM (Table 5) are displayed as contour maps (Figure 4). The contour maps display the probability of predicting fish presence given particular pairwise relationships. For example, a segment where the maximum upstream gradient is greater than 200% and the maximum downstream step (bankfull widths) is lower than 0.38m has a high (90-100%) probability of being classified as containing fish. Additionally, the logistic regression test for interaction effects between pairs of covariates demonstrates that segments with a maximum downstream gradient greater than 71% and a low maximum upstream step bankfull width has a low probability of being classified as containing fish (Figure 4). The highest effect importance measure for maximum upstream gradient and maximum downstream step (bankfull width) was 0.007 (Table 5; Figure 4). While effective gradient had an overall low interaction strength, near zero (Figure 5), the interaction between effective gradient and maximum downstream gradient was one of the highest at 0.005 (Table 5). Maximum downstream gradient, maximum upstream gradient, maximum step bankfull width, bankfull width (BFW10.m), and the average sustained upstream gradient had the highest overall interaction strengths of all covariates (Figure 5).

Table 4. Comparison between the full random sample using random forest and interaction forest. Interaction forest performed marginally better.

Model Type	Number of Trees	AUC	Accuracy (PCC)	Sensitivity	Specificity	Kappa
Random Forest†	300	0.90	89.63%	0.94	0.87	0.79
Interaction Forest	300	0.94	94.17%	0.90	0.98	0.88

†Random forest model tuning parameters and performance metrics using the *Random Full* data set with substrate and unit features removed.

AUC = area under the curve; kappa =a measure of agreement between predicted presences and absences; PCC = proportion of presence correctly classified; sensitivity = proportion of presence correctly classified; specificity = the proportion of absence correctly classified

Table 5. Effect importance measure (EIM) values for the interaction between variable pairs (A and B).

Variable A	Variable B	EIM
Max.Up.Grad	Max.Dn.Step.BFW10	0.007
Max.Dn.Grad	Max.Up.Step.BFW10	0.005
Eff.Grad	Max.Dn.Grad	0.005
Max.Up.Grad	Max.Up.Step.BFW10	0.004
Avg.Sus.Grad.Up	Max.Dn.Grad	0.004

Avg= average; BFW = bankfull width; BFW10 = BFW for 5 segments below, the current segment, and four segments above; DelEff = Change in effective; Dn = downstream; Eff = effective; Grad = gradient; Ht = height; m = meter; Step = ?:Sus = sustained; Up = upstream

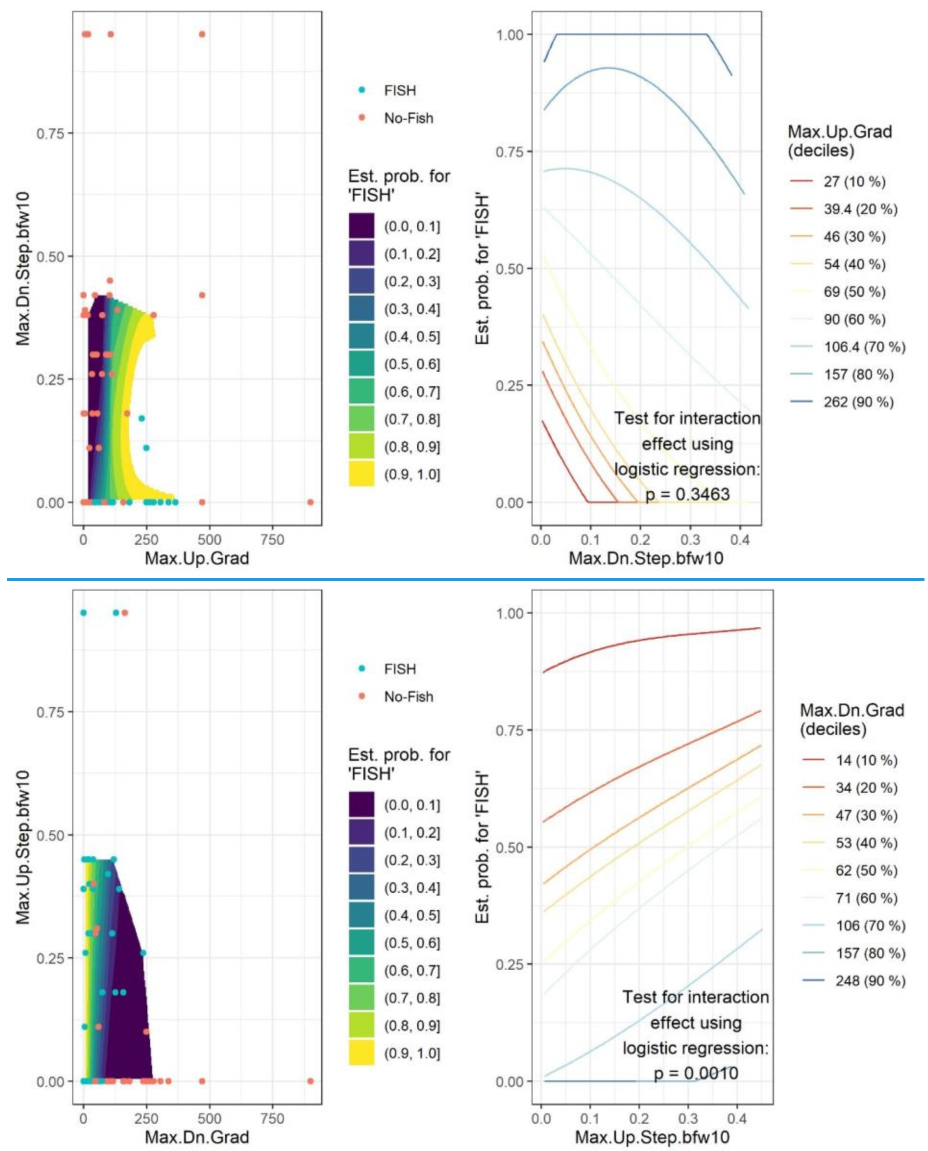

Max.Dn.Step.bfw10
Max.Up.Grad
FISH
No-Fish
Est. prob. for 'FISH'
(0.0, 0.1]
(0.1, 0.2]
(0.2, 0.3]
(0.3, 0.4]
(0.4, 0.5]
(0.5, 0.6]
(0.6, 0.7]
(0.7, 0.8]
(0.8, 0.9]
(0.9, 1.0]
Est. prob. for 'FISH'
Max.Dn.Step.bfw10
Max.Up.Grad (deciles)
27 (10 %)
39.4 (20 %)
46 (30 %)
54 (40 %)
69 (50 %)
90 (60 %)
106.4 (70 %)
157 (80 %)
262 (90 %)
Test for interaction effect using logistic regression: p = 0.3463
Max.Up.Step.bfw10
Max.Dn.Grad
FISH
No-Fish
Est. prob. for 'FISH'
(0.0, 0.1]
(0.1, 0.2]
(0.2, 0.3]
(0.3, 0.4]
(0.4, 0.5]
(0.5, 0.6]
(0.6, 0.7]
(0.7, 0.8]
(0.8, 0.9]
(0.9, 1.0]
Est. prob. for 'FISH'
Max.Up.Step.bfw10
Max.Dn.Grad (deciles)
14 (10 %)
34 (20 %)
47 (30 %)
53 (40 %)
62 (50 %)
71 (60 %)
106 (70 %)
157 (80 %)
248 (90 %)
Test for interaction effect using logistic regression: p = 0.0010

Figure 4. Interaction contour and cross section plots for pairs of variables with the highest effect importance measure values. P-values on each cross-section plot are overly optimistic according to the *diversityForest* manual. Since both predictors are continuous and the outcome is categorical, *diversityForest* employs a 2-dimensional LOESS regression. The color gradient in the contour plot ranges from purple at 0 (no-fish) to yellow at 1 (fish).

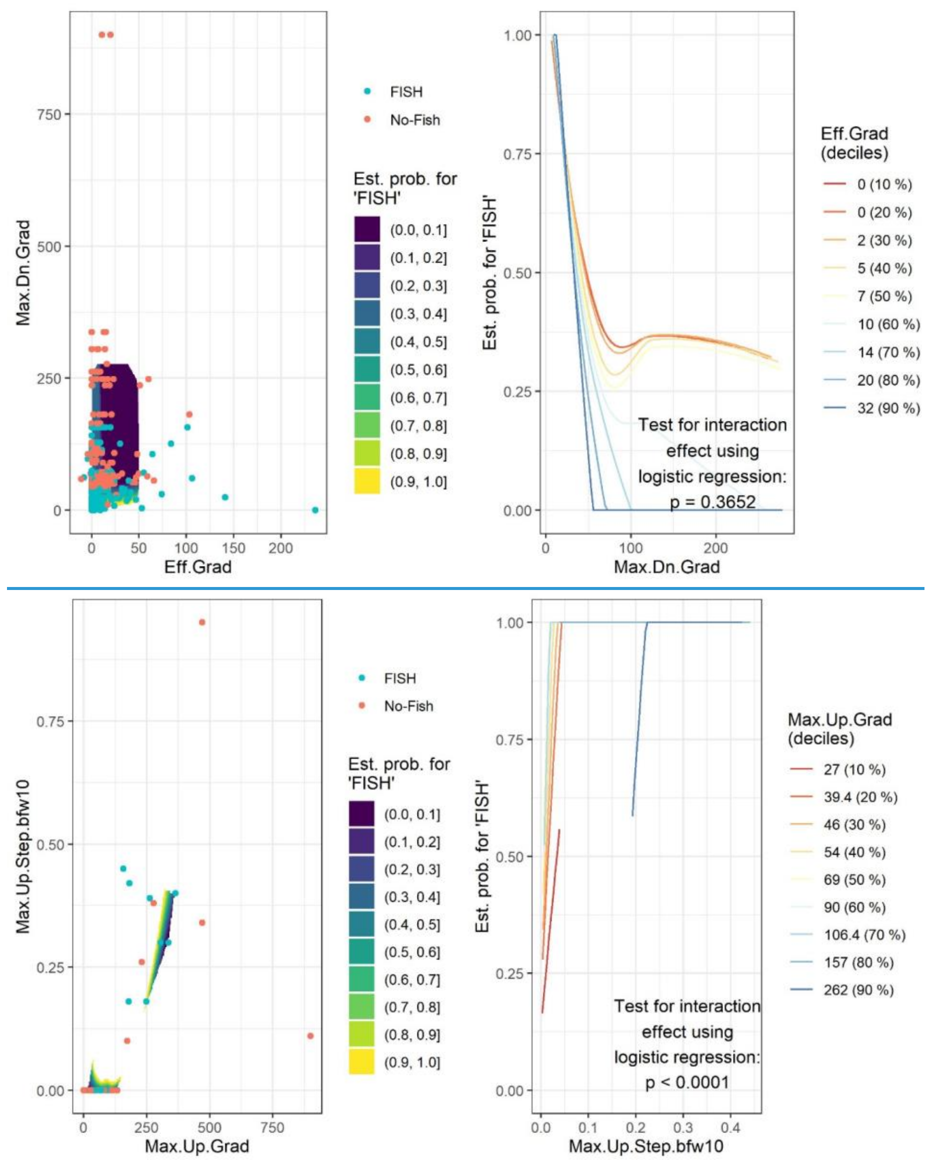


Figure 4. (*continued*) Interaction contour and cross section plots for pairs of variables with the highest effect importance measure values. P-values on each cross-section plot are overly optimistic according to the *diversityForest* manual. Since both predictors are continuous and the outcome is categorical, *diversityForest* employs a 2-dimensional

LOESS regression. The color gradient in the contour plot ranges from purple at 0 (no-fish) to yellow at 1 (fish).

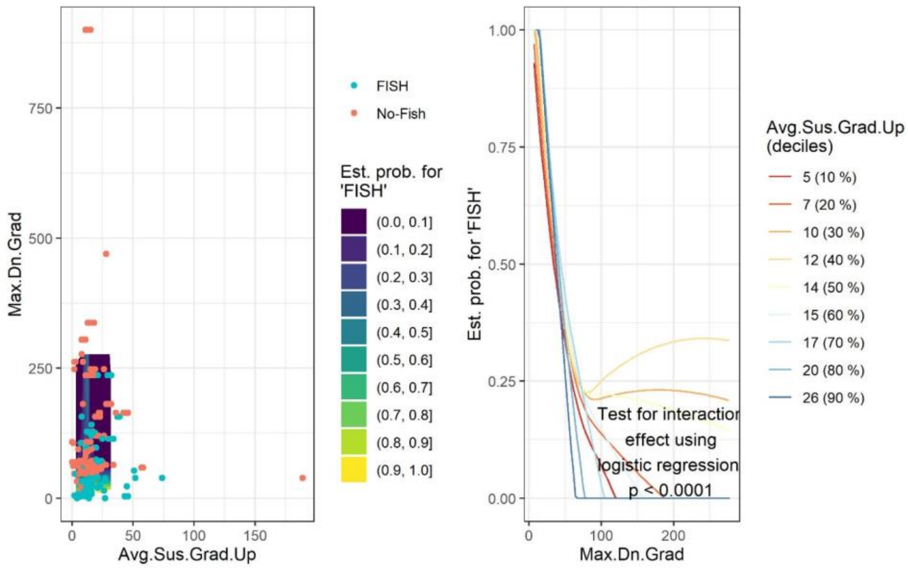


Figure 4. (*continued*) Interaction contour and cross section plots for pairs of variables with the highest EIM values. P-values on each cross-section plot are overly optimistic according to the *diversityForest* manual. Since both predictors are continuous and the outcome is categorical, *diversityForest* employs a 2-dimensional LOESS regression. The color gradient in the contour plot ranges from purple at 0 (no -fish) to yellow at 1 (fish).

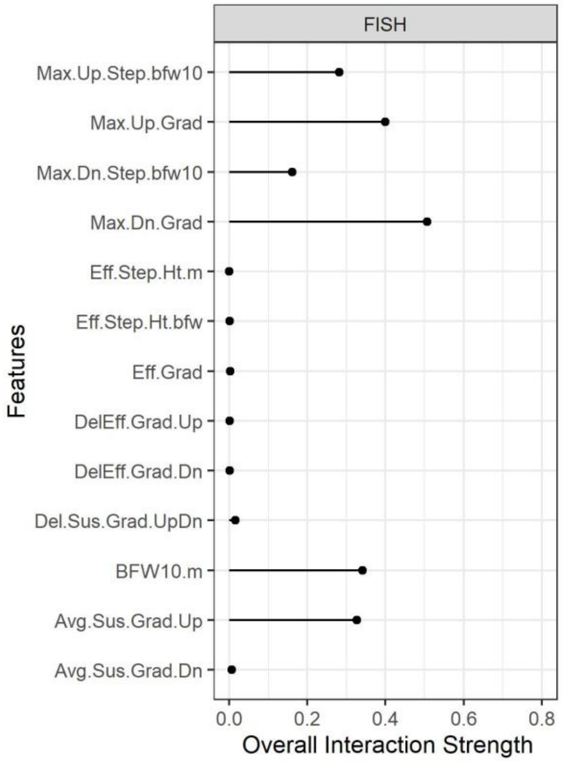


Figure 5. Overall interaction strength using package *iml* for each stream characteristic.

Evaluating Forest Practice Board proposed Potential Habitat Break Criteria

Four criteria sets were examined related to the FPB criteria: options A, B, and C and the combined set of unique criteria used in the All Criteria model. Because no stream segments in the pilot data set met TestCriterion2 or TestCriterion3, these criteria were not included in the evaluations of options A, B, or C. Similarly, the random forest model for All Criteria combined contained only the five criteria that were met by any segments in the pilot data set (TestCriterion1, TestCriterion4, TestCriterion5, TestCriterion6, and TestCriterion7).

Predicting fish presence using the four criteria sets resulted in low accuracy, sensitivity, specificity, and kappa parameters (Table 6). This was most notable for Option B that exhibited an accuracy of 48.36%. The confusion matrices in Table 7 display the comparisons of observed fish presence versus. the fish presence based on FPB criteria. This result seems largely driven by the large number of false negative results (observed = fish; prediction = no-fish) for Option A, and false positives (observed = no-fish, prediction = fish) for All Criteria and Option B. Option C had nearly equal numbers of false negatives and false positives. Evaluating the FPB criteria using random forest models resulted in low accuracies and poor model performance (Table 8).

Table 6. Prediction evaluation of the four criteria compared to observed fish presence.

	AUC	Accuracy (PCC)	Sensitivity	Specificity	Kappa
All Criteria*	0.54	49.28%	0.84	0.24	0.07
Option A	0.60	62.52%	0.40	0.79	0.20
Option B	0.52	48.36%	0.74	0.29	0.03
Option C	0.59	59.8%	0.52	0.65	0.18

* Includes only TestCriterion1, TestCriterion4, TestCriterion5, TestCriterion6, and TestCriterion7 because no stream segments met the condition for TestCriterion2 or TestCriterion3.

AUC = area under the curve; kappa = a measure of agreement between predicted presences and absences; PCC = proportion of presence correctly classified; sensitivity = proportion of presence correctly classified; specificity = the proportion of absence correctly classified

Table 7. Confusion matrices for each of the four criteria sets and the observed data.

All Criteria*		Observed: Fish	Observed: No-Fish
Prediction	Fish	811	997
Prediction	No-Fish	160	313

Option A		Observed: Fish	Observed: No-Fish
Prediction	Fish	391	275
Prediction	No-Fish	580	1,035

Option B		Observed: Fish	Observed: No-Fish
Prediction	Fish	721	928
Prediction	No-Fish	250	382

Option C		Observed: Fish	Observed: No-Fish
Prediction	Fish	509	455
Prediction	No-Fish	462	855

* Includes only TestCriterion1, TestCriterion4, TestCriterion5, TestCriterion6, and TestCriterion7 because no stream segments met the condition for TestCriterion2 or TestCriterion3.

Table 8. Parameters from model tuning in *caret* and model performance from validation testing for TestCriterion1, TestCriterion2, and TestCriterion3.

	mtry	Maxnodes	Number of Trees	AUC	Accuracy (PCC)	Sensitivity	Specificity	Kappa
All Criteria*	5	5	250	0.58	59.73%	0.53	0.62	0.13
Option A	1	5	250	0.64	64.77%	0.61	0.66	0.24
Option B	1	5	250	NA	57.77%	NA	0.58	0
Option C	2	5	250	0.62	62.14%	0.62	0.62	0.21

* Includes only TestCriterion1, TestCriterion4, TestCriterion5, TestCriterion6, and TestCriterion7 because no stream segments met the condition for TestCriterion2 or TestCriterion3.

AUC = area under the curve; kappa = a measure of agreement between predicted presences and absences; Maxnodes = maximum number of nodes; mtry = optimum number of covariates; PCC = proportion of presence correctly classified; sensitivity = proportion of presence correctly classified; specificity = the proportion of absence correctly classified

Variables of importance differed little between each for each criteria set. TestCriterion1, the barrier cutoff of 20%, was the most useful predictor for the models for All Criteria, Option A, and Option C (Figure 6). TestCriterion5 and TestCriterion6, followed by the gradient of 10%, exhibited low variable importance in the All Criteria and Option C models (Figure 6), but was deemed unimportant for the Option B model by the *Boruta* algorithm (Figures 6 and 7). Similarly, TestCriterion7 was deemed important in the All Criteria model by random forest and *Boruta*, but unimportant for the Option C model (Figures 6 and 7).

TestCriterion1 relates to sustained stream gradient and parallels the results from the random forest *Full Random* model (Figure 1) where variables related to gradient were deemed most important and the interaction forest model (Figure 5) where gradient variables had strongest interaction strength. TestCriterion5 is also related to gradient but did not emerge as strong of a predictor as TestCriterion1. TestCriterion6 relates to obstacles and step heights and was found most important when paired with TestCriterion1 (Figure 7). This finding is corroborated in both the random forest models and the interaction forest model. Step-related variables were consistently in the top five most important variables (Figures 1–3), and the strongest interaction strength existed between gradient-related variables and step variables (Figure 4). More specifically, the interaction strengths were strongest for maximum upstream or downstream gradient variables and the bankfull width at the step. Width changes are encapsulated in TestCriterion7, and the width criteria were deemed important for the All Criteria model.

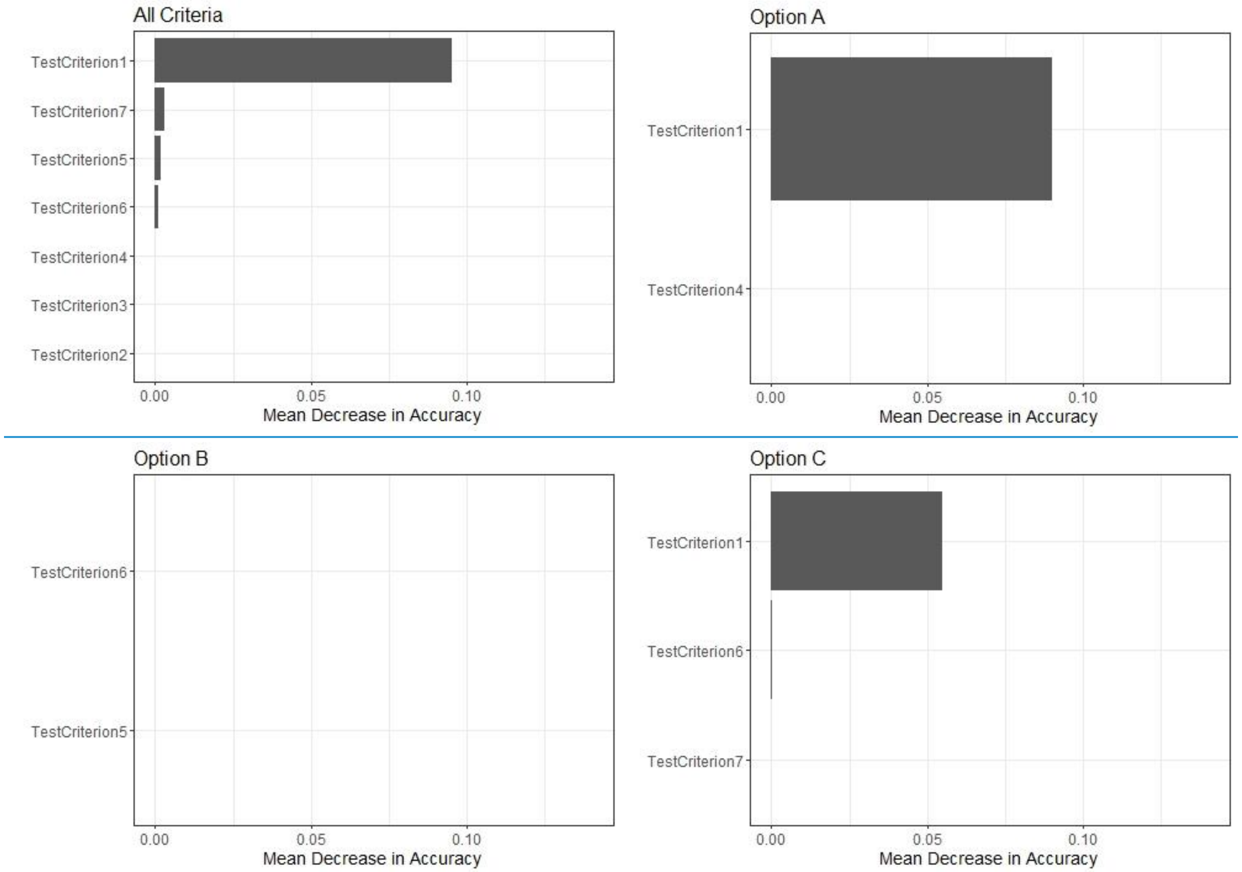


Figure 6. Variable importance from random forest models for criteria sets based on options from the Washington Forest Practices Board outlined in Table 3. Visualized using package vip (Greenwell and Boehmke 2020).

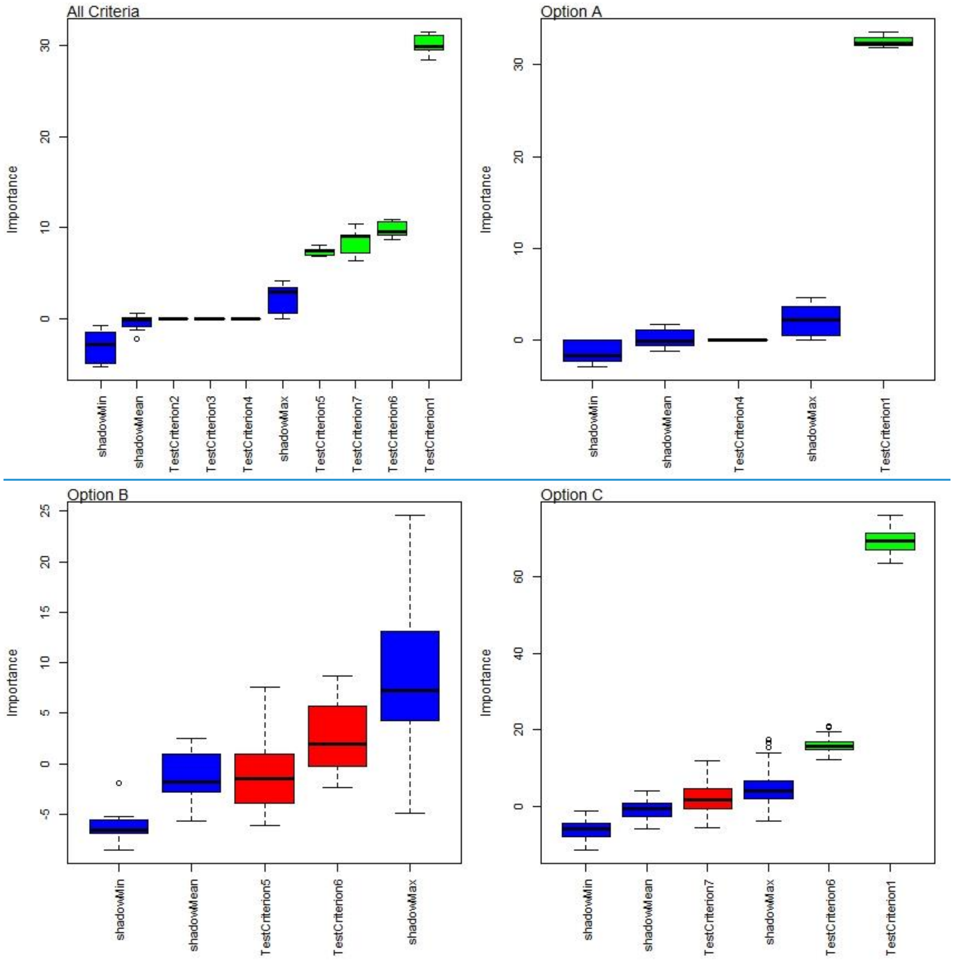


Figure 7 .Variable importance validation using *Boruta*. Variable importance is displayed for each criterion described by the Washington Forest Practices Board in Table 3. Features in green were deemed important by *Boruta*, yellow are tentatively important, red are unimportant, and blue are called shadow features from *Boruta*. Shadow features are shuffled copies of all features to add randomness to the *Boruta* algorithm.

DISCUSSION

In this example analysis with pilot data, we demonstrated that random forest models and interaction forest models can classify presence of fish on stream segments in Washington State with greater than 90% accuracy. More importantly, random forest and interaction forest enabled a multivariate analysis to determine which variables best described areas with fish and without fish, including stream gradient, steps or barrier height, bankfull width, and other characteristics. Interaction forests outperformed random forest models based on model accuracy, kappa, and specificity, and helped identify key parameters that in combination influence end of fish. These results correspond with findings from a comparison of random forest and interaction forest classification models on 220 different data sets (Hurnung and Boulesteix 2022). Given the lower accuracy of classifying eastern Washington stream segments, a larger sample in conjunction with an interaction forest approach may improve model performance in future analyses.

Evaluating the FPB criteria by comparing observed fish presence for sets of criteria with random forest models resulted in relatively low accuracies. Reducing a continuous habitat covariate to a binary indicator may reduce the predictive power of the random forest model if the cutoff point used to create the binary indicator is not closely associated with the end of fish. TestCriteria 2 and TestCriteria3 were not met by any segments in the pilot data set, but we anticipate that these criteria will be incorporated into future analyses. To more adequately evaluate the criteria following additional sampling, we recommend measuring all steps, not just those presumed to cause a barrier to reduce bias in the gradient and barrier parameters.

While we have demonstrated that certain stream features are useful predictors of fish versus non-fish habitat, the ultimate objective of this analysis is to describe the inflection point or transition between these two states. The partial dependency plots (Figure 3) reveal where the probability of fish occurrence cross for several high importance parameters. This graphical assessment provides a sense of where the PHB occurs. However, this application of partial dependency plots is not how use is intended for random forest classification protocols. Box and violin plots in Appendix A were added to qualitatively assess the stepwise progression from average fish habitat, habitat near end of fish, and habitat without fish. These plots in conjunction with random forest may provide an empirical basis for establishing criteria for habitat covariates.

Detecting and describing PHBs within streams may require an alternative analysis in conjunction with the random forest approach already applied. To quantitatively identify the parameter values associated with the end of fish and establish PHBs, we recommend conducting additional analysis with a methodology intended to identify inflection points, such as changepoint analysis, generalized additive models, or covariate-dependent hidden Markov models (HMM), to identify and describe PHBs.

Changepoint analyses are used to statistically detect transitions between particular states (i.e., fish, no-fish; Killick et al. 2012). Traditionally, changepoint analyses are used for time-series data, but can also be applied to sequence data (Muggeo 2008), such as stream segments. Changepoint analysis has been used to determine thresholds for solute concentrations related to nutrient movement in Arctic watersheds (Shogren et al. 2022), migration behavior of bull trout (Lewis 2021), transitions in incubation behavior of ducks (Johnstone 2021), and a myriad of other applications described in Khodadadi and Asgharian's (2008) annotated bibliography. Johnstone (2021) combined changepoint analyses and generalized additive models to quantify duck incubation patterns related to landscape covariates, such as roads, cover, habitat, and air temperature. Unlike random forest analysis, changepoint analyses can detect a threshold, such as the transition between fish and no-fish segments. However, applying this approach for our research objectives may be challenging, as the threshold cannot be determined for several covariates simultaneously and cannot identify which covariates best describe the threshold. Additionally, the changepoint would be calculated for each stream separately.

Thresholds may also be identified with generalized additive models (GAMs). Large et al. (2013) used a GAM with a smoothing term for the year covariate, and then calculated first and second derivatives of the smoothed trend function to identify trends and thresholds, respectively, for a set of 11 marine ecosystem indicators that demonstrated a significant smoothed trend. Similarly, GAMs could be modeled as functions of continuous habitat covariates to identify points at which the probability of fish presence changes for values above or below a habitat variable threshold. However, these thresholds cannot be identified for categorical variables.

The goal of this analysis is to characterize the features associated with the end of fish in each stream. An appropriate analysis would include the predictive capacity of the random forest with the ability to identify a threshold as with the changepoint analysis or GAM approach. A covariate-dependent HMM may therefore be a suitable approach. HMMs are probabilistic models that quantitatively predict and describe underlying patterns in system states using spatially-sequential or time-series data (McClintock et al. 2020). HMMs are a special case of state-space models that describe a finite number of states or conditions that change across space or time. The system or state changes are deemed "hidden" or unobservable. While habitat breaks along streams can be identified through field observation, the dynamics driving that transition from fish to no-fish are hidden.

HMM frameworks are flexible for a variety of ecological applications, including survival analyses (Williams et al. 2002), describing birth and death processes from capture-recapture data (Schmidt et al. 2015), disease dynamics (Benhaiem et al. 2018), life-history trade-offs (Lloyd et al. 2020), animal movement (Patterson et al. 2009), and many others reviewed by McClintock et al. (2020). Mahmud et al. (2020) compared a covariate-dependent HMM to a classification tree for precipitation events in Bangladesh. Their model incorporated weather station data from five separate regions to characterize the conditions that resulted in rain events. Their research demonstrated that a HMM approach performed more consistently than a classification tree. HMMs can accommodate either time-series data or spatially-sequential data. The model relies on the assumption that the probability of state (fish or no-fish) at location t in a sequence is dependent upon the state at t-1 or the previous sequence (stream segment; McClintock et al. 2020). In a

covariate-dependent HMM, the probability of being in a "fish" state at segment *t* depends on the state (fish or no-fish) at segment *t*-1 and the covariates measured on segment *t*.
HMMs are intended for analyses with a finite number of hidden states (i.e. fish, no-fish), and to accommodate sequential data (i.e. continuous stream segments), determine features associated with hidden states, and identify the change-points/transitions between states (the habitat breaks) (McClintock et al. 2020).

A covariate-dependent HMM (e.g., Mahmud and Islam 2019) would incorporate the sequential nature of the data and enable inference on the habitat covariates leading to a transition from fish to no-fish. An HMM analysis would involve the following steps: 1) fitting the HMM to identify the hidden states of fish/no-fish, 2) examining the stream segments, 3) finding the change-point/transition from fish to no-fish, and 4) determining the covariate patterns leading to the transition. In summary, random forest modeling may be used in conjunction with the HMM approach to identify variables associated with the fish/no-fish state and then apply the HMM with the identified habitat covariates to locate features associated with the end of fish from spatially-sequential stream segments.

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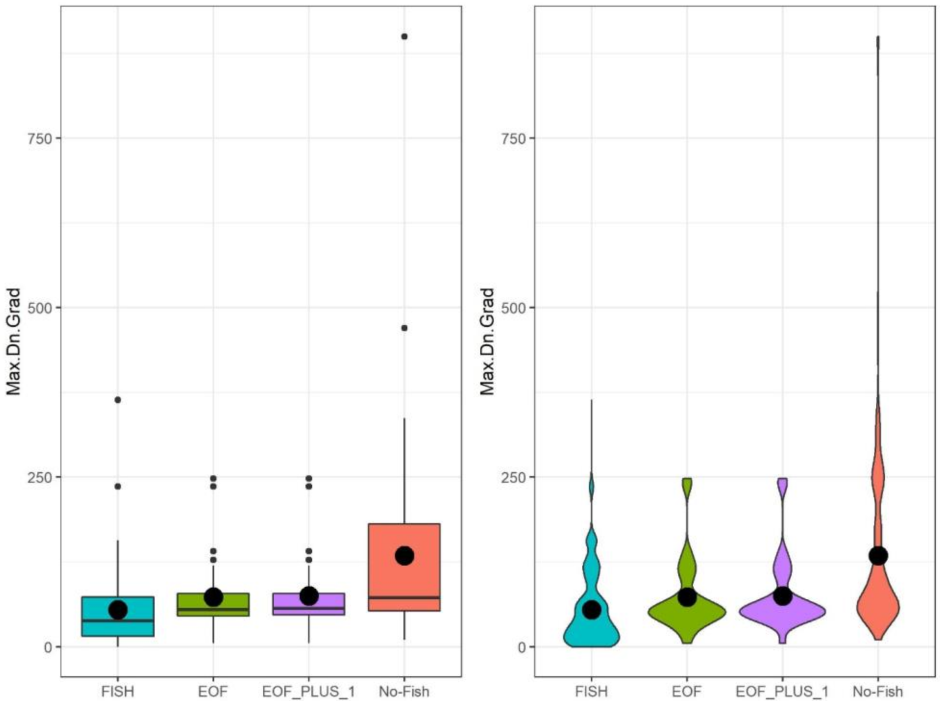
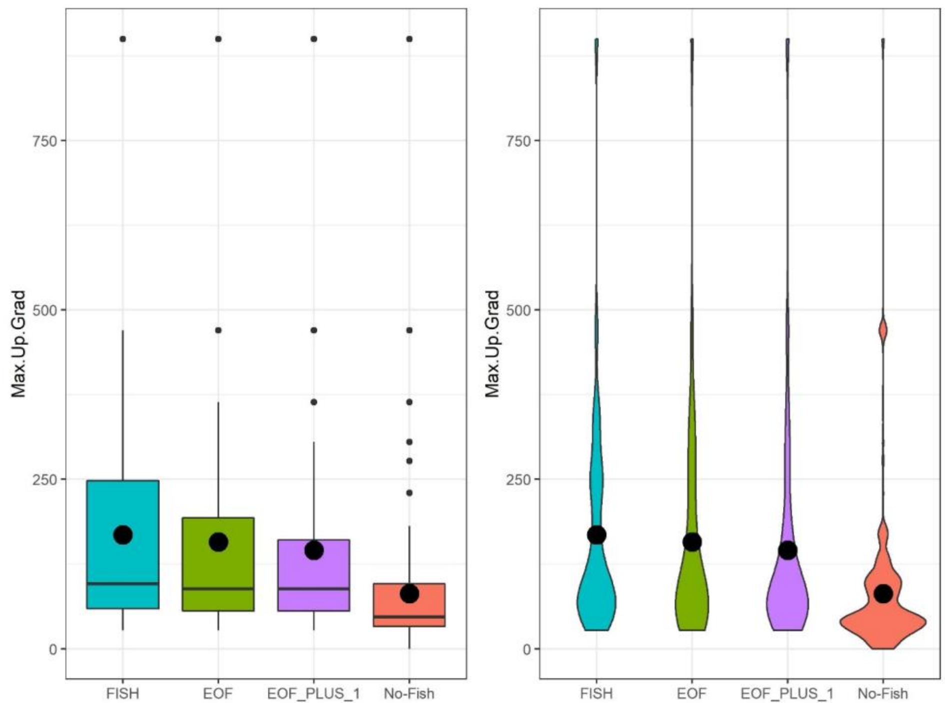
Appendix A. Additional Figures

Box and violin plots for the distribution of variables deemed important by the random forest analyses. The plots include stream segments designated as fish, end of fish (EOF), one segment above end of fish (EOF+1; EOF_Plus_1), and no-fish. Segments at EOF and EOF+1 were not double counted, and thus represent the average for a particular value at the potential habitat break. Figures are in the order of variable importance based on the *Full Random* model.

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No-Fish
Max.Up.Grad
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250
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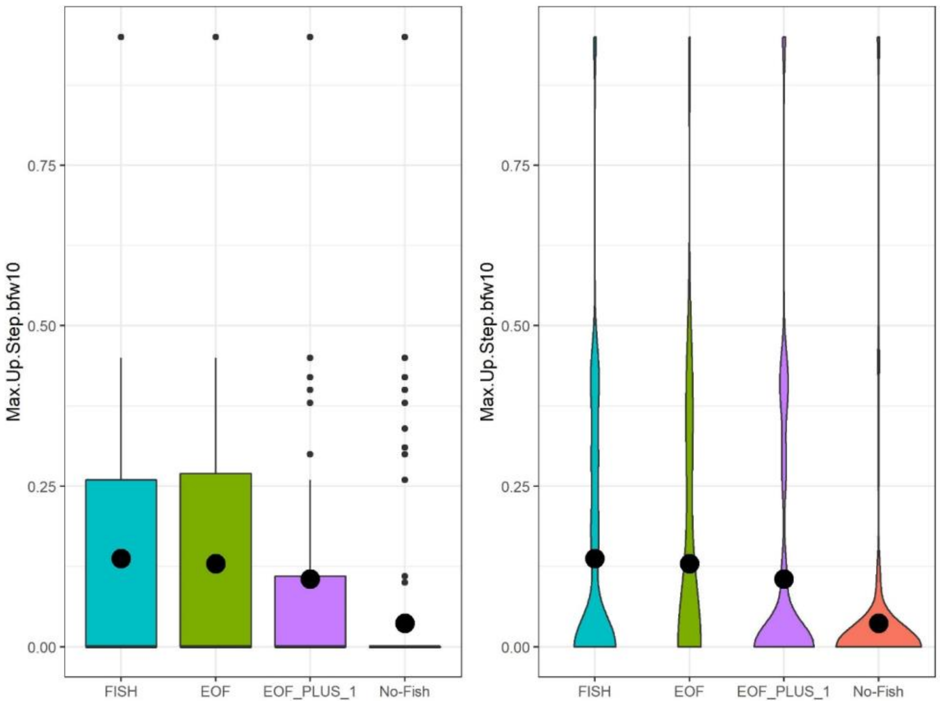
EOF_PLUS_1
No-Fish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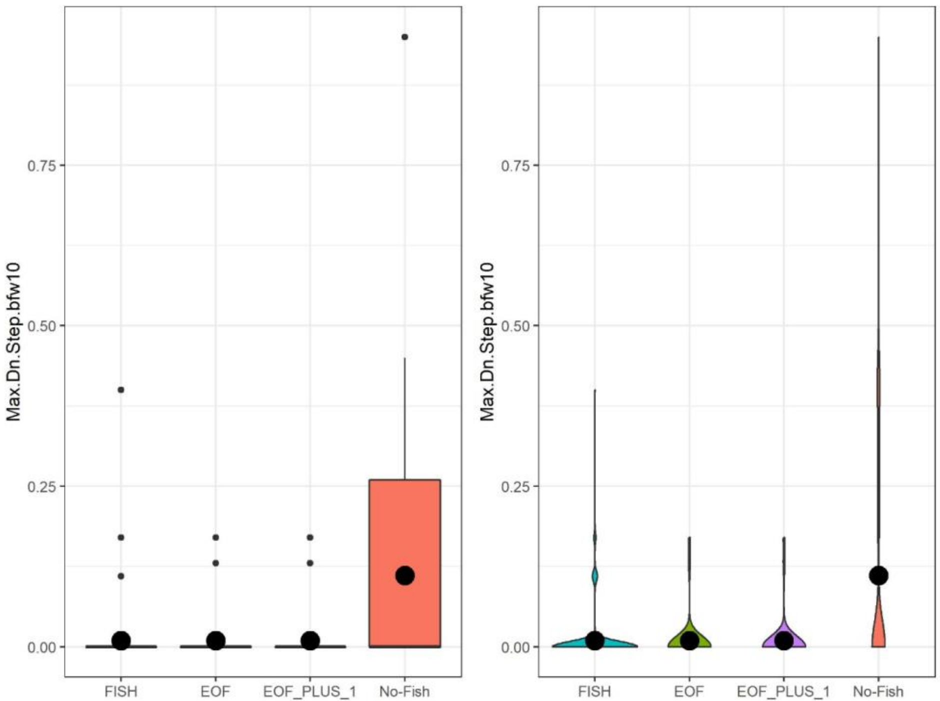
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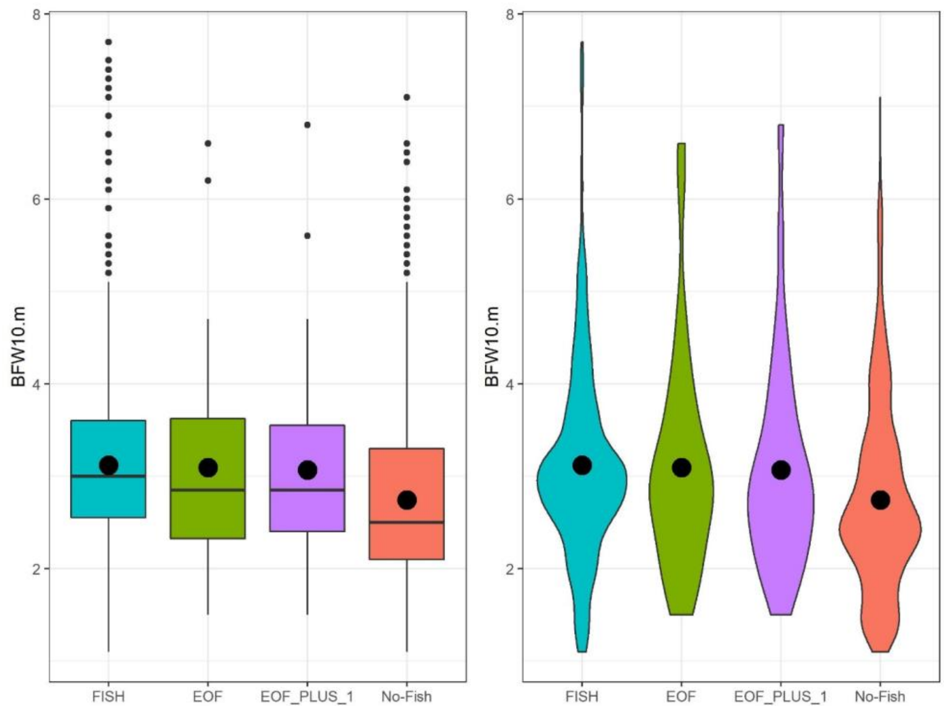
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4
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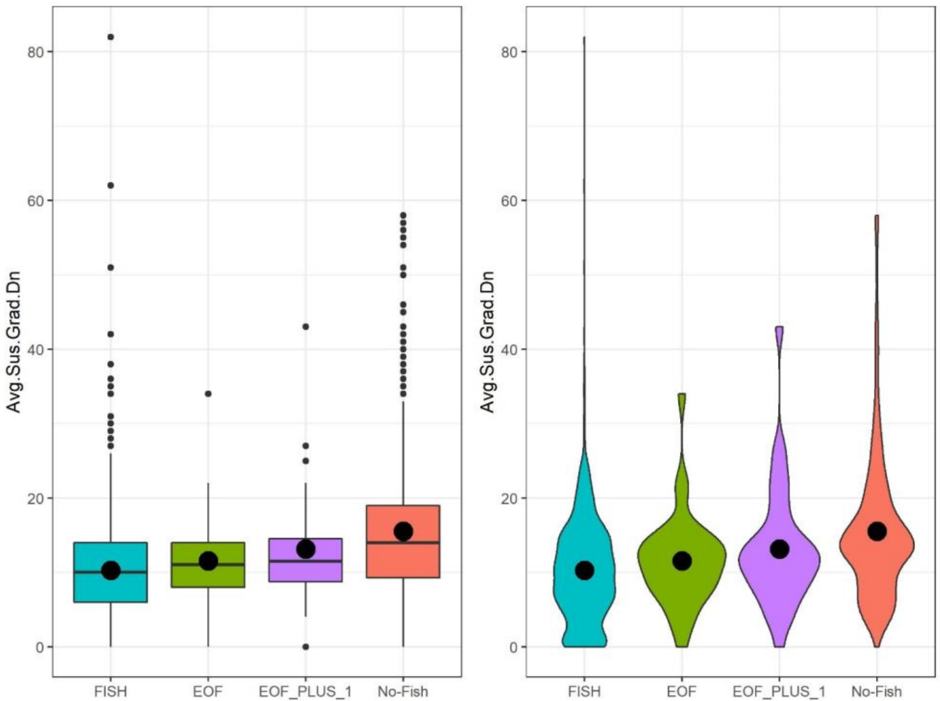
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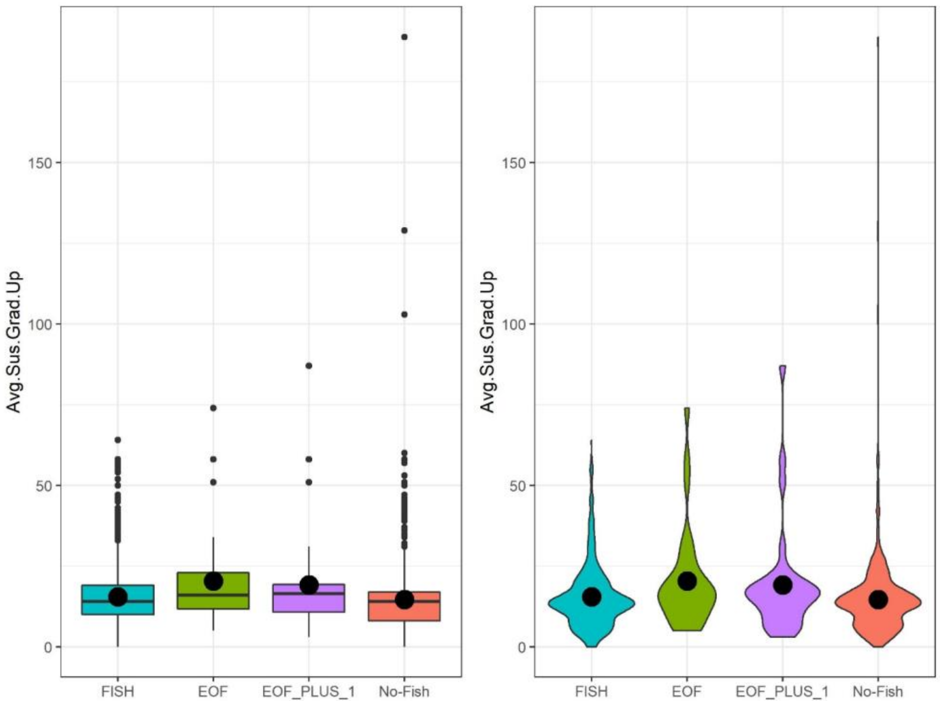
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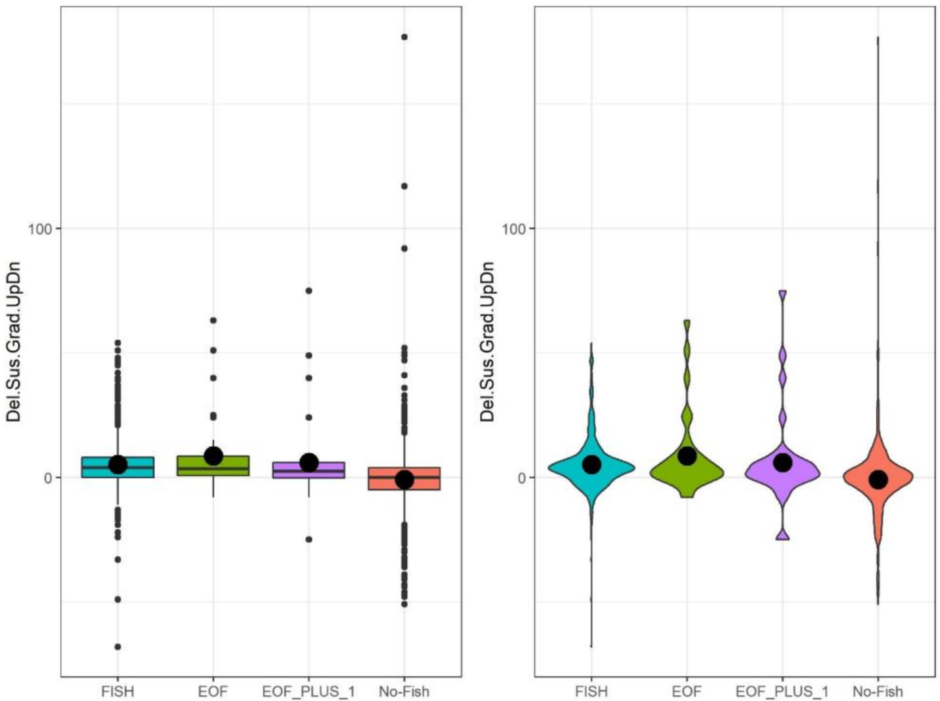
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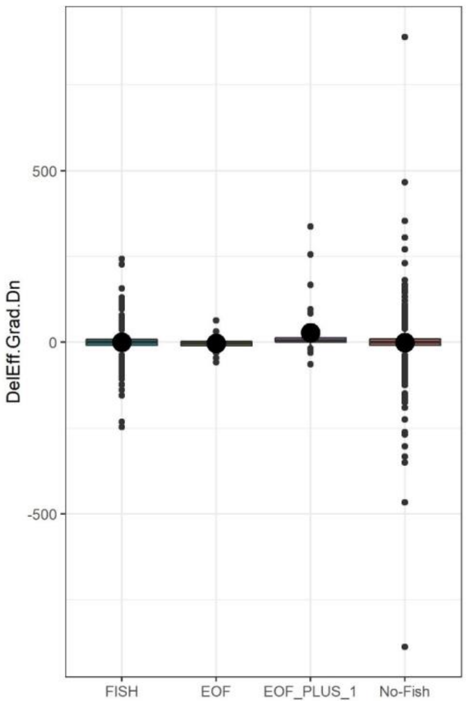
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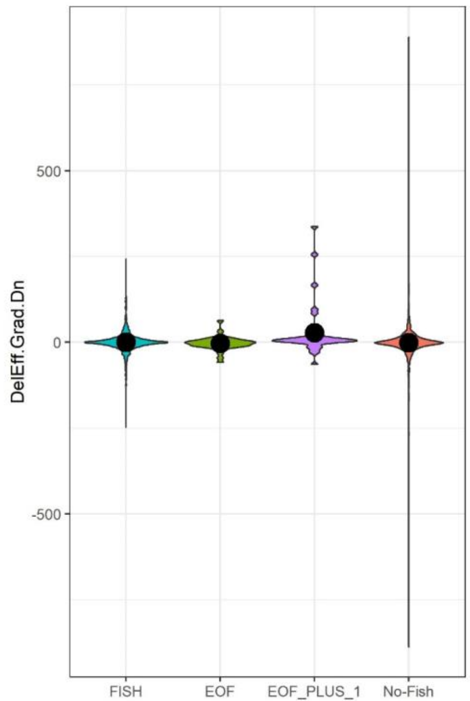
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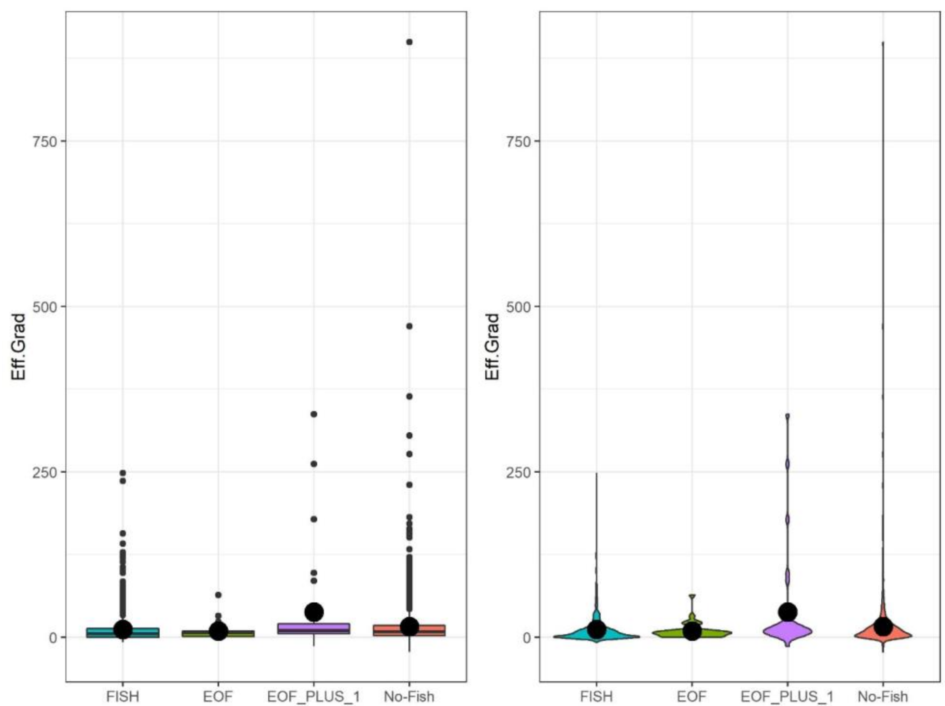
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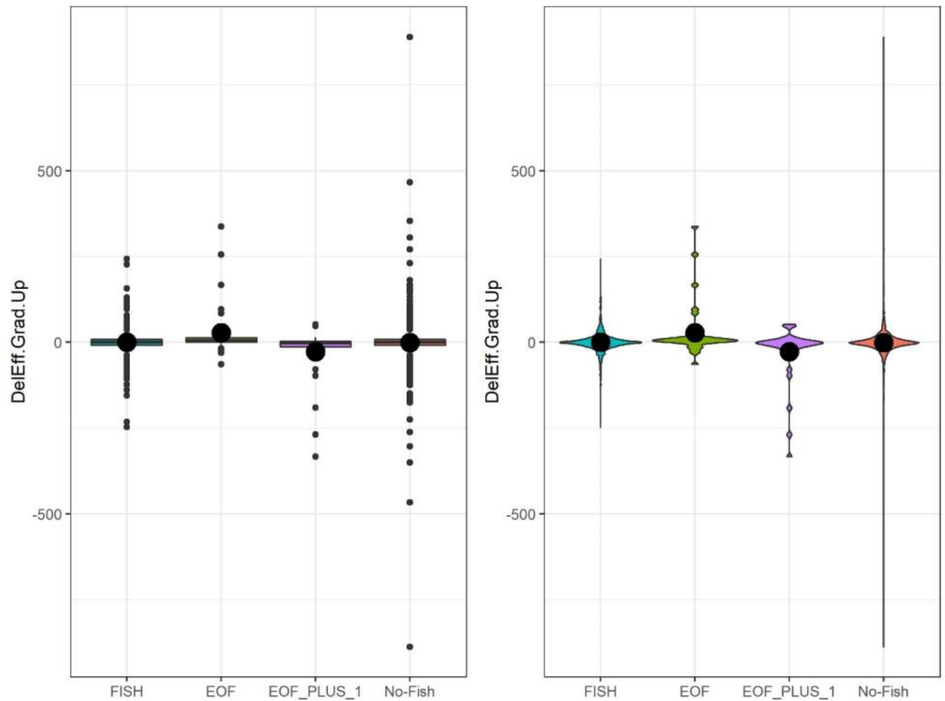
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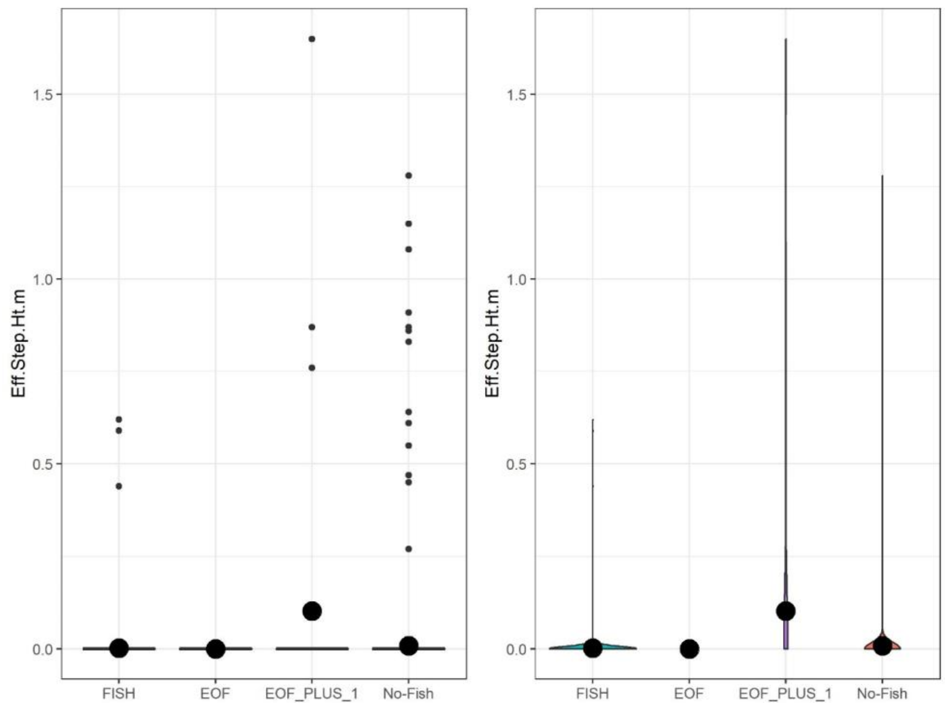
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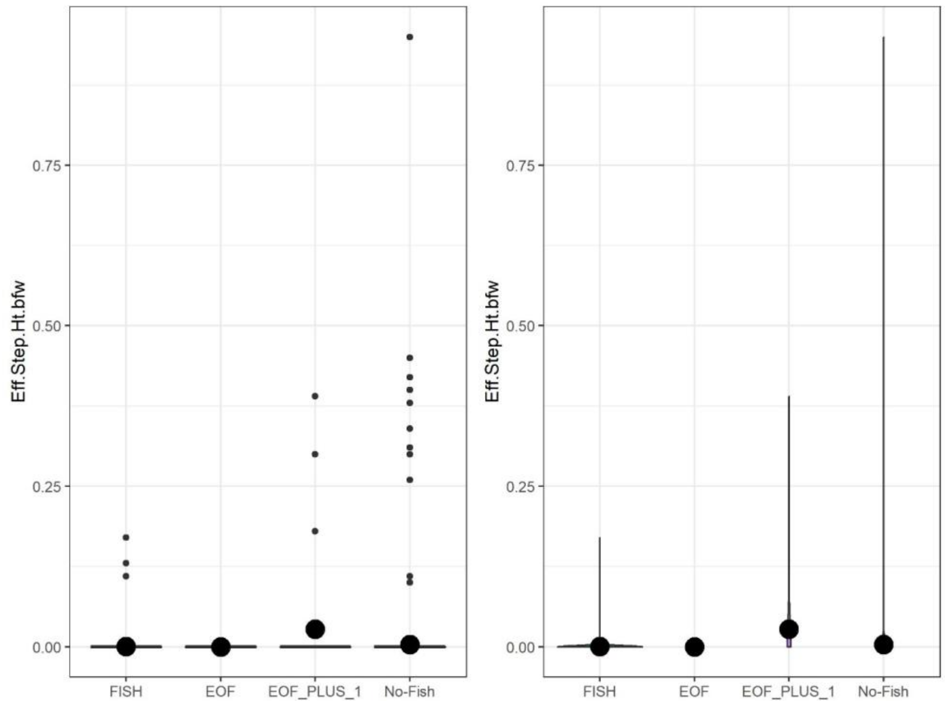
No-Fish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0.50
0.25
0.00
FISH
EOF
EOF_PLUS_1
No-Fish

Appendix B. Modeling Covariate Data Dictionary

Variable	Definition
StreamName	copied main stream data to each tributary for separate evaluation, consistent with pilot study analysis.
Station	Survey station
DelDistance	Length of segment (m)
CumulativeDistance	Distance from start of survey (m)
Substrate	
Comments	
EOFpt	In methodology, be clear that this is the last segment WITH fish; EOF pt is at top of segment.
FISH/NO-FISH	fish are assumed to use all segments below the EOF station
Flow Condition	flowing/dry
UnitLabel	Unit type modified for use in PHB analysis Riffle/Pool/Step Step defined as >150% gradient based on pilot study. Step-Pool is when gradient is >8% and Substrate = Fines or Sand (not implemented) If Unit = Riffle but elevation change is <= 0, Unit was changed to Pool
EffectiveGrad_pct	Based on Effective Elevation Change, which sets pool elevations to the elevation of the tail-out (riffle or step downstream of pool) Add in functionality to figure out (presumed) head of pool and calculate gradient above that only? Subgroup decided 6/16/2022 not to bother for the purposes of this pilot, but real study must.

Variable	Definition
EffectiveStepHeight_m	Change in effective elevation (elevation - previous elevation or pool residual elevation) for a segment having gradient >=150%
EffectiveStepHeight_BFW	Change in effective elevation (elevation - previous elevation or pool residual elevation) for a segment having gradient >=150% reported in multiples of the BFW10 at each station (col BA)
DelEffectiveGradFromDnstrmSeg	Change in effective gradient from downstream segment
DelEffectiveGradToUpstrmSeg	Change in effective gradient to next segment upstream
BFW10_m	includes 10 stations, per WAC definition (as close as we can reasonably get); five stations below, the present station, and four stations above; bedrock units excluded from average calculation
AvgSusGradDnstrm	includes 20 segments downstream (19 stations below plus this one) stations, per WAC definition (as close as we can reasonably get)
AvgSusGradUpstrm	includes 20 segments upstream (20 stations above) stations, per WAC definition (as close as we can reasonably get)
MaxDnstrmGrad	Requires that data be ordered by StreamName and Station Maximum segment effective gradient downstream of each station

Variable	Definition
MaxUpstrmGrad	Requires that data be ordered by StreamName and Station Maximum segment gradient upstream of each station
MaxDnstrmStep_BFW10	The maximum step downstream of the present station, in multiples of BFW10
MaxUpstrmStep_BFW10	The maximum step upstream of the present station, in multiples of BFW10
BFW_Dn10	Average of the BFW for the 10 segments downstream of current station (m)
BFW_Up10_m	Average of the BFW of the 10 segments upstream of the current station (m)
BFW_Up20_m	Average of the BFWs for the 20 segments upstream of the current station (m)
BFW_Up20_ft	Average of the BFWs for the 20 segments upstream of the current station (ft)

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Appendix ~~C~~D. Potential for a concurrent eDNA study

The original study design (~~Roni et al.~~PHB Science Panel 2019) included a proposed collaborative complementary study with the U.S. Forest service to compare environmental DNA (eDNA) and electrofishing to identify fish habitat. A separate pilot for that proposed complementary study was completed in 2020 (Penaluna 2020).

The project team explored ways to include further eDNA components into this study design. The team determined that the best option would be to recommend that an additional complementary study is developed by the Adaptive Management Program that utilizes the sample sites and the fish location data that are collected in this study. This companion study can further compare electrofishing and eDNA as methods for determining the location of the upper extent of fish use, as well as different methods for eDNA collection and analysis, and can take advantage of the lessons learned from the pilot study. Conducting a complementary study in conjunction with the PHB study might save time, money, and resources.

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Appendix ED. Budget

Budget estimate from DNR PM Anna Toledo as of February 18, 2022. Estimates are based on figures updated from the FY19 study design, expenditures from the FY19 pilot study, and existing contract budgets for similar work. These estimates may change based on revisions made during CMER, ISAG, and ISPR reviews.

Task	Expenditures FY17-FY21	FY22	FY23	FY24	FY25	FY26	FY27	FY28	FY29	Total
Study design, coordination, site reconnaissance, permitting, crew training		31,247	69,250	163,679	114,167	30,512	30,918	N/A	N/A	439,773
Field sampling – Spring/summer (350 sites)					723,697	723,433	737,901	N/A	N/A	2,185,031
Field sampling – Fall/winter (175 sites: fixed + rotating panels)					N/A	176,389	179,917	183,515	N/A	539,821
Crew variability (10% of sites – all crews)					57,944	55,028	56,129	25,505	N/A	194,606
Data collection equipment					183,600	27,540	27,540	27,540	N/A	266,220
Data analysis and reporting				12,485	39,202	67,832	69,189	94,796	61,229	344,733
Project Management				9,364	15,918	16,236	16,561	10,930	4,460	73,469
Total	**398,702**	**31,247**	**69,250**	**185,528**	**1,134,529**	**1,096,970**	**1,118,155**	**342,286**	**65,689**	**4,442,355**

Budget Comparison

Comparison of original study design and revised study design budgets. Original study design budget and tasks in grey.

Task	Original Study Design Totals	Revised Study Design Totals	Notes
Study design, coordination, site reconnaissance, permitting, crew training	421,900	439,773	Revised budget accounts for a 2% yearly increase for inflation/COLA throughout all line items, which was not accounted for in the original budget.
Field sampling – Spring (245 sites)	1,519,000		Total site visits (original): 529 Total site visits (revised): 525
Field sampling – Spring/summer (350 sites)		2,185,031	
Field sampling – Summer (82+60)	460,151		
Field sampling – Fall (82+60); pilot in FY 19	581,151		
Field sampling – Fall/winter (175 sites: fixed + rotating panels)		539,821	
Crew variability (10% of sites – all crews)	115,000	194,606	
Data collection equipment		266,220	Data collection equipment was not a separate line item in original budget.
eDNA sampling (82 sites 3 times)	50,000		eDNA recommended as a complementary study, removed from revised budget.
eDNA Lab Analysis and reporting	164,000		
Data analysis and reporting	180,163	344,733	Budget updated to reflect updated time estimate for analysis and reporting.
Project Management	72,669	73,469	
Total	3,564,034	4,442,355	

Appendix F. Data Tables and Attribute Descriptions

Table Error! No text of specified style in document.**-1. Site selection initial fish survey start point attributes – GIS-derived**

Attribute	**Source**	**Units**	**Description**
SiteID	GIS		Identifier from DNR hydro layer
Stream Name	GIS		Local name
Stream Order	GIS		Strahler Stream Order #
Ecoregion	GIS		DNR Natural Heritage Level III [Northwest Coast, Puget Trough, North Cascades, West Cascades, East Cascades, Okanogan, Canadian Rocky Mountains, Blue Mountains]
Side of State	GIS		Location relative to cascade crest [East, West]
Latitude of currently mapped F/N break	GIS	dd	WGS1984
Longitude of currently mapped F/N break	GIS	dd	WGS1984
Elevation of currently mapped F/N break	GIS	m	
Currently mapped F/N break point type	GIS		Terminal or Lateral
Broad-scale land use class	GIS		Industrial timberland, USFS, small private timberland, conservation forest, residential, other forestry, other non-forest
30-year annual and seasonal normal precipitation	GIS	mm	PRISM model and data from neighborhood reference rain gauges
30-year annual and seasonal normal flows for one or more neighboring gauged streams	Calculated	cms	30-year or as close to that as possible; the point is to be able to place the survey year flow levels in the broader long-term flow context
Seasonal Sampling Scheme	Assigned		Fixed or rotating panel, and if rotating, which of (3) years
Optimal Spring Survey Timing	Assigned		Based on information provided by local/regional experts
Optimal Seasonal Survey Timing	Assigned		Based on information provided by local/regional experts

Table Error! No text of specified style in document.-2. **Site field attribute table**

Attribute	**Source**	**Units**	**Description** (detail in Methods Manual)
SiteID	GIS		Identifier from DNR Hydro layer
Landscape Reference Point (LRP)	Field		Narrative description of a permanent topographic/physical feature used to help locate the FRPs and LFPs
LRP Latitude	Field	dd	Decimal degrees; WGS 1984
LRP Longitude	Field	dd	Decimal degrees; WGS 1984
Fixed Reference Point (FRP)	Field		Narrative description of FRP closest to initial LF point relative to permanent topographic/physical feature such as a confluence point with mainstem, tributary junction, etc.
FRP Latitude	Field	dd	Decimal degrees; WGS 1984
FRP Longitude	Field	dd	Decimal degrees; WGS 1984
FRP Elevation	Field	m	Will be baseline from which habitat surveys are conducted
Notes	Field		Any features significant at a site level

Table Error! No text of specified style in document.-3. **Last Fish survey data for each survey event; Last Fish point (EOF) will be baseline from which habitat surveys are conducted.**

Attribute	**Source**	**Units**	**Description** (detail in Methods Manual)
SiteID	GIS		Identifier from DNR Hydro layer
SurveyID	Assigned		Which survey (year/season)
Date			
Weather Conditions	Field		sunny, rainy, snowy, cloudy
Air Temp	Field	C	
Field Crew			
Fish Survey Start Point	Field	dd, m	Lat, Long, Elev at fish survey start point
Fish Survey Start Water Temp	Field	C	
Stream Conductivity	Field	uS/cm	
Electrofisher Setting	Field		
Fish Survey End Point	Field	dd, m	Lat, Long, Elev at fish survey end point
Fish Survey End Water Temp	Field	C	
EOF Latitude	Field	dd	Decimal degrees; WGS 1984
EOF Longitude	Field	dd	Decimal degrees; WGS 1984
EOF Elevation GPS	Field	m	NAD83

Attribute	Source	Units	Description (detail in Methods Manual)
EOF Stream Distance From Topographic Reference Point (RP)	Field	m	EOF point field-identifiable location relative to a permanent topographic or physical feature such as a confluence point with mainstem, tributary junction, etc., if feasible Also identify reference objects to help locate
EOF Date-Time	Field		YYYY-MM-DD-24-hour; Standard Time;
EOF WaterTemp	Field	C	To nearest 0.5 C
Upstream-Most Fish Species/Family	Field		When it can be determined (salmonid; sculpin (cottid); stickleback; mudminnow; etc)
Fish Size Category	Field	mm	<25mm, 25-75mm, 75-150mm, >150mm
EOF Point Type	Field		Terminal or Lateral
EOF Flow Status	Field		Flowing, Dry
EOF Habitat Unit Type	Field		Pool, Riffle, Step-Pool, Step (>=2' vertical)
EOF Measurement Point Type	Field		e.g. crest of tailout; bottom of pool; head of pool
Potential Reason (Feature) for Last Fish	Field		If present and identifiable; eg – deformable obstacle/debris jam; dry channel; falls; other; etc
Vertical/Near-vertical Obstacle(s) present?	Field	Yes/No	
Lateral/Terminal Stream	Field		May vary based on last fish location
EOF Riparian Stand Type (RB)	Field		Watershed Analysis methods
EOF Riparian Stand Type (LB)	Field		Watershed Analysis methods
Streamside Land Use Class at EOF	Field		Industrial timberland, USFS, small private timberland, conservation forest, agriculture, residential, other forestry, other non-forest
Notes	Field		Include potential explanatory features (CMZ, alluvial fan, debris flow, end of channel)
EOF Elevation GIS	GIS	m	Lidar-based
EOF Drainage Area	GIS	km^2	
EOF Distance-to-Divide	GIS	m	
EOF Valley Aspect	GIS		Compass points [N, NE, E, SE, S, SW, W, NW]
EOF Valley Width	GIS	m	
EOF Valley Confinement	Calculated		Valley Width/Channel Width ratio
EOF Geologic Competence	GIS		Resistant or Erodible, based on classifications provided for Hard/Soft Rock Type N studies [Competent/Medium/Incompetent]

Attribute	**Source**	**Units**	**Description** (detail in Methods Manual)
Total Annual Precipitation for Current Hydrologic Year	nearby reference rain gauges	mm	from nearby reference rain gauges (see Table **Error! No text of specified style in document.**-1~~Table F-1~~)
Total Seasonal Precipitation for Survey Season	nearby reference rain gauges	mm	from nearby reference rain gauges
% of AnnualNormal Precipitation	Calculated	%	Total annual P for survey year/annual Normal
% of Seasonal Normal Precip	Calculated	%	Total seasonal P for survey season/seasonal Normal
Total Annual Streamflow for Current Hydrologic Year	nearby reference stream gauges	cms	from nearby reference stream gauges (see Table **Error! No text of specified style in document.**-1~~Table F-1~~)
Total Seasonal Streamflow for Survey Season	nearby reference stream gauges	cms	from nearby reference stream gauges (see Table **Error! No text of specified style in document.**-1~~Table F-1~~)
% of AnnualNormal Streamflow	Calculated	%	Total annual Q for survey year/annual Normal
% of Seasonal Normal Streamflow	Calculated	%	Total seasonal Q for survey season/seasonal Normal

Table Error! No text of specified style in document.-**4**. **Habitat survey site field attributes**

Attribute	**Source**	**Units**	**Description**
SiteID	GIS		Identifier from DNR Hydro layer
SurveyID	Assigned		e.g., 2024-spring; 2025-fall, etc.; precise form of survey ID to be determined
Survey Date	Field		
Weather	Field		sunny, rainy, snowy, cloudy
Field Crew	Field		
Bottom of Survey (BOS) Latitude	Field, GPS	dd	WGS84
BOS Longitude	Field, GPS	dd	WGS84 (Negative dd for west)
BOS Elevation	Field, GPS	m	NAD83

Top of Survey (TOS) Latitude	Field, GPS	dd	WGS84
TOS Longitude	Field, GPS	dd	WGS84 (Negative dd for west)
TOS Elevation	Field, GPS	m	NAD83
Turnpoint Numbers and Locations	Assigned during survey		Turnpoints may be set on a Station, in which case the station can be identified as the location, or may be set outside of the channel thalweg, in which case the location relative to the previous turnpoint must be recorded.

Table Error! No text of specified style in document.-**5. Habitat Survey Channel Survey Station Measured Attributes**

Attribute	**Source**	**Units**	**Description**
SiteID	GIS		Identifier from DNR Hydro layer
SurveyID			
Station Number	Assigned during survey		sequential numbering of survey stations from Bottom of Survey
Turnpoint Number	Assigned		Turnpoint ID (see Table **Error! No text of specified style in document.**-4~~Table F-4~~) from which station location is measured
Station Distance from Turnpoint	Measured	m	
Station Azimuth from Turnpoint	Measured	deg	
Station Elevation from Turnpoint	Measured	m	
Last Fish Segment	Observation of Monument	LF	Observation of Last Fish monument from Fish Survey occurs within measurement segment; not necessarily at the surveyed station if LF is monumented within a homogeneous segment
Water Depth	Measured	m	Instantaneous depth at station along thalweg (not BFD)
Channel Width	Measured	m	At bankfull elevation
Wetted Width	Measured	m	Water's edge
Flow Status	Observation		Dry, Flowing
Dominant Substrate	Ocular estimate	Categ.	Categorical (e.g. sand, gravel, cobble, boulder, bedrock, silt/clay/fines, wood)
Habitat Unit Type	Ocular estimate	Categ.	Pool, Riffle, Step, Step-Pool, Obscured
Station Point Type	Ocular estimate	Categ.	e.g. crest of tailout; bottom of pool; head of pool (may be blank)

Obstacle Type	Ocular estimate	Categ.	Vertical/Non-Vertical
Step Forming Medium	Ocular estimate	Categ.	Categorical (e.g. wood (log, debris, roots), hardpan, boulder, bedrock)
Tributary Junction	Observation	1	Flag if present; place station at point

Table Error! No text of specified style in document.-**6. Stream habitat survey segment calculated attributes**

Attribute	**Source**	**Units**	**Description**
SiteID			
SurveyID			
Station #			
Segment Length [m]	Calculated	m	Calculated distance from Station n-1 to Station n; segment data relate to the segment below the station (i.e., "stations" are the upstream point of the segment)
Distance from Bottom of Survey			Running total of segment lengths from BOS (BOS = Station 0)
Above, at, or Below Last Fish Segment	Calculated	US/DS/LF	Calculated based on location of LF segment from Table **Error! No text of specified style in document.**-5~~Table F-5~~; required for calculation of other attributes
Fish Presence	Calculated	FISH/NO-FISH	Assigned to segments based on location relative to LF point; needed for random forest models
Bankfull Width 10 (=bfw10)	Calculated	m	Average of bankfull widths from 4 stations downstream, current station, and 5 stations upstream, in approximate conformance with Forest Practices rule
Average BFW for 10 * bfw10 upstream	Calculated	m	Average of bankfull widths for a distance of 10*bfw10 upstream Required to test for FPB criteria
Average BFW for 20 * bfw10 upstream	Calculated	m	Average of bankfull widths for a distance of 20*bfw10 upstream Required to test for FPB criteria
Average BFW for 10 * bfw10 downstream	Calculated	m	Average of bankfull widths for a distance of 10*bfw10 downstream Required to test for FPB criteria
Segment Thalweg Bed Rise (Vertical Distance)	Calculated	m	Vertical Distance from Beg to End of Segment; calculated as change in elevation from station n-1 to station n
Thalweg Bed Gradient	Calculated	%	Segment Thalweg Bed Elevation Change/Segment Length
Effective Elev	Calculated	m	Calculated for pools based on pool tailout elevation; that (residual pool) elevation is translated to the

Attribute	Source	Units	Description
			segment upstream of the pool to determine the "effective" bottom elevation of the next (n+1) stream segment, for the purpose of calculating "effective, fish-eye" gradient of the n+1 segment
Effective Segment Rise		m	elevation of segment end minus the Effective Elevation, if there is one; otherwise, equals segment thalweg bed rise
Effective Segment Gradient		%	Effective Segment Rise/Segment Length
Effective Gradient Change From Downstrm Segment			Effective Gradient change from n-1 to n
Effective Gradient Change To Upstrm Segment			Effective Gradient difference from n to n+1
Maximum Effective Gradient Downstream from EOF	Calculated	%	Calculated from segment data using effective gradients
Length of Max Dnstrm Gradient Feature	Calculated	m	Calculated from segment data using effective gradients
Max sustained5 gradient downstrm	Calculated		Max of the running Minimum gradient feature over 5 cw; using effective gradients
Sustained Gradient Downstream	Calculated	%	Minimum gradient feature over 20 cw downstream of station n (including segment n); using effective gradients
Maximum Gradient Upstream of EOF	Calculated	%	Calculated from segment data; using effective gradients
Length of Max upstrm Gradient	Calculated	m	Calculated from segment data
Max sustained5 gradient upstrm	Calculated		Max of the running Minimum gradient feature over 5 cw; using effective gradients
Sustained upstream gradient	Calculated	%	Minimum gradient feature over 20 cw upstream of station n; using effective gradients
Delta Sustained Gradient upstrm	Calculated	%	Sustained upstream gradient – Sustained downstream gradient
Maximum Step Height Upstream	Calculated	bfw10s	
Maximum Step Height Downstream	Calculated	bfw10s	

Attribute	Source	Units	Description
Pool Frequency Upstream of Segment	Calculated	pool count/ bfw10	Calculated over 20*bfw10 upstream of current station
Pool Spacing Upstream of Segment	Calculated	m	Calculated over 20*bfw10 upstream of current station
Pool Frequency Downstream of Segment	Calculated	pool count/ bfw10	Calculated over 20*bfw10 downstream of current station
Pool Spacing Downstream of Segment	Calculated	m	Calculated over 20*bfw10 downstream of current station

Table Error! No text of specified style in document.-7. **Habitat survey attributes calculated for stream at each survey**

Attribute	Source	Units	Description
SiteID	GIS		Identifier from DNR Hydro layer
SurveyID			
LF Distance from BOS	Calculated	m	
LF Elevation GIS	GIS	m	Lidar-based
LF Drainage Area	GIS	km^2	
LF Distance-to-Divide	GIS	m	
LF Valley Aspect	GIS		Compass points [N, NE, E, SE, S, SW, W, NW]
LF Valley Width	GIS	m	
LF Valley Confinement	Calculated		Valley Width/Channel Width ratio
LF Geologic Competence	GIS		Resistant or Erodible, based on classifications provided for Hard/Soft Rock Type N studies [Competent/Medium/Incompetent]
Total Annual Precipitation for Current Hydrologic Year	nearby reference rain gauges	mm	from nearby reference rain gauges (see Table **Error! No text of specified style in document.**-1~~Table F-1~~)
Total Seasonal Precipitation for Survey Season	nearby reference rain gauges	mm	from nearby reference rain gauges
% of AnnualNormal Precipitation	Calculated	%	Total annual P for survey year/annual Normal

% of Seasonal Normal Precip	Calculated	%	Total seasonal P for survey season/seasonal Normal
Total Annual Streamflow for Current Hydrologic Year	nearby reference stream gauges	cms	from nearby reference stream gauges (see Table **Error! No text of specified style in document.**-1~~Table F-1~~)
Total Seasonal Streamflow for Survey Season	nearby reference stream gauges	cms	from nearby reference stream gauges (see Table **Error! No text of specified style in document.**-1~~Table F-1~~)
% of AnnualNormal Streamflow	Calculated	%	Total annual Q for survey year/annual Normal
% of Seasonal Normal Streamflow	Calculated	%	Total seasonal Q for survey season/seasonal Normal
Habitat Unit Upstream of LF	Calculated		
Effective Gradient of Segment Upstream of LF	Calculated	%	
BFW of segment Upstream of LF	Calculated	m	
Delta Sustained Gradient upstrm of LF	Calculated	%	Sustained upstream gradient – Sustained downstream gradient
Maximum Gradient Downstream from LF	Calculated	%	Calculated from segment data
Length of Max Dnstrm Gradient Feature	Calculated	M	Calculated from segment data
Maximum Sustained Gradient Downstream from LF	Calculated	%	Defined based on 20 bfw (multiple versions)
Length of Max Sustained Dnstrm Gradient Feature	Calculated	Multiples of bfw (m)	Calculated from segment data
Max Gradient Change Downstream of LF	Calculated	%	Calculated from segment data
Maximum Gradient Upstream of LF	Calculated	%	Calculated from segment data
Length of Max upstrm Gradient	Calculated	m	Calculated from segment data

Max sustained upstream gradient	Calculated	%	Sustained for minimum of 20*bfw10 to be in line with PHB proposals
Length of Max sustained upstream gradient	Calculated	m, bfw10	Length of the above in meters and also in multiples of bfw10
Max Sustained Gradient Change upstrm of LF	Calculated	%	Calculated from segment data; each gradient sustained for 20* bfw10
Maximum Step Height Upstream of LF	Calculated	bfw10s	
Maximum Step Height Downstream of LF	Calculated	bfw10s	
Pool Frequency Upstream of Segment	Calculated	count/ bfw10	Calculated over 20*bfw10 upstream of current station
Pool Spacing Upstream of Segment	Calculated	m	Calculated over 20*bfw10 upstream of current station
Pool Frequency Downstream of Segment	Calculated	pool count/ bfw10	Calculated over 20*bfw10 downstream of current station
Pool Spacing Downstream of Segment	Calculated	m	Calculated over 20*bfw10 downstream of current station

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