Managing Expectations from Intensively Monitored Watershed Studies

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ABSTRACT

Intensively monitored watershed (IMW) studies whose intent is to quantify habitat restoration effects on salmonid populations have been underway in the Pacific Northwest, USA, for more than two decades, but the perception among some natural resource management and funding organizations is that such studies are too costly and results too equivocal to justify continuation. Lack of population-level response to habitat improvements by target species in some IMWs may be related to incomplete knowledge of factors regulating fish abundance, excessively prolonged restoration application periods, underappreciation of natural environmental and population variability, failure to carry out restoration at a sufficiently large scale within a watershed, lack of sufficient time to document post-treatment response, or to an actual failure of the restoration activities in those locations to achieve population recovery objectives. Yet, knowledge gained from IMWs has yielded important insight into long-term salmon and steelhead responses to different types of restoration and to the importance of placing freshwater habitat improvements in the context of changes in anadromous salmonid survival and growth during other life history stages. Scientists, funding organizations, and policy makers should be aware of hurdles in carrying out IMW studies, and realize the potential value of IMWs as long-term barometers of the status and trends of salmon populations and their habitats in watersheds where restoration activities are occurring. This requires a commitment to prolonged monitoring and an acknowledgment that environmental recovery after habitat restoration may take decades.

INTRODUCTION

In the US Pacific Northwest (PNW), a network of Intensively Monitored Watersheds (Figure 1) has been established to evaluate the effects of habitat restoration on populations of imperiled anadromous salmonids, many of which are listed under the U.S. Endangered Species Act. IMWs generally possess small to mid-size streams and consist of watersheds in which habitat restoration treatments such as migration barrier removal, large wood addition, floodplain reconnection, or riparian revegetation have been applied. In some cases, treated watersheds are paired with a nearby control watershed that remains untreated. While many studies of stream restoration efficacy examine habitat and fish abundance at the scale of individual restoration sites, IMWs use a long-term monitoring approach to evaluate responses of salmonid populations in watersheds where multiple stream restoration activities have taken place over a period of years and typically employ an experimental design to help detect a restoration signal. The most commonly employed experimental design is before-after-control-impact (BACI), although some IMWs use simpler treatment/control or before/after approaches (Bennett et al. 2016) or more complex progressive staircase design (Walters et al. 1988). The time scale for monitoring varies; however, some Pacific Northwest IMWs have been monitored since the 1990s. Bennett et al. (2016) provide a detailed and comprehensive summary of the locations, types of treatments, and target fish species that have been studied.

Over the typical projected 20 to 30-year life span of an IMW the cumulative monitoring expenditure for an IMW can be relatively high, with monitoring costs sometimes exceeding US $100,000 annually. With such a long-term study trajectory, funding organizations may ask what they are getting for their investment, while policy makers may wonder why it takes so long to see results. Moreover, to date, few IMWs have shown an increase in target species population size (Bilby et al. 2022), and reasons for this apparent lack of success are typically multiple and can remain unclear. The lack of target-species population response may result from not restoring those habitat conditions that are most constraining the target population or to an inability to detect, from a monitoring perspective, a population increase. Alternatively, stream restoration may benefit the target population, yet those benefits are not sufficient to offset other factors outside of natal watersheds such as ocean conditions or harvest activities, contributing to overall salmon population declines. Regardless of the reasons, potential outcomes of an IMW study should be clearly understood and appreciated both by scientists involved in designing and carrying out the monitoring, and by those who have supported IMWs and who will learn from the results.

Our objective in this paper is to review key expectations that typically underpin IMWs as an approach to evaluating habitat restoration success, even if they are not explicitly identified. We also examine what has been learned about the IMW study design in the Pacific Northwest over the past two decades, and suggest how lessons from the past can be used to develop realistic expectations for existing and future IMW endeavors, here and elsewhere. We hope these findings are useful to scientists involved in or contemplating an IMW study, to managers and other stakeholders wishing to know how well fish habitat restoration programs are working, and to funding organizations whose long-term support for IMWs is essential.

IMW EXPECTATIONS

Habitat managers often assume the ultimate measure of success for a suite of stream and estuarine habitat restoration actions is an increase in the number of adult salmon and steelhead returning to spawn. The management goal of documenting population response through IMW research includes four implicit expectations with regards to aquatic habitat restoration for target species. The first expectation is that there is a direct relationship between habitat conditions and adult returns. The second is that the most significant habitat problems are addressed with sufficient restorative effort. The third is that the restoration signal will be larger than the noise created by natural variability. The fourth expectation is that a fish population response will occur within the timeframe of the restoration and subsequent monitoring.

There has been an important distinction between management and scientific objectives for IMWs. While expectations have been to document salmon recovery at the watershed scale, the objectives of long-term scientific monitoring have focused on determining whether there are significant changes in habitat quality and population abundance following restoration, and if so, by how much. Habitat managers may view an inability of post-restoration monitoring to demonstrate population increases as study failure, while scientists may see the absence of measurable improvements as important evidence to assist in identifying which environmental attributes most limit target species in spawning and rearing habitats.

Expectation 1. Habitat conditions regulate fish responses

The biological response to habitat improvement efforts is critical to discerning the effectiveness of restoration activities (Roni et al. 2002). There is an expectation that as restoration improves freshwater habitat, an increase in the abundance of the targeted fish populations should be observed. This expectation is driven by a history of studies showing that habitat capacity and quality influence salmon abundance at all freshwater life stages, and that integration of densitydependent and density-independent survival processes across the entire salmon life cycle ultimately exerts a strong influence on abundance of adult spawners (Pess and Jordan 2019; Jorgensen et al. 2021; Beechie et al. 2021). In general, habitat capacity regulates the maximum number of adults, eggs, or juveniles that can be produced at any life stage. However, habitat quality also influences abundance through subsequent life stages, and either capacity or survival in certain life stages may limit population size (Moussalli and Hilborn 1986). If, for example, winter rearing habitat for Coho Salmon is scarce, winter habitat capacity may limit overall abundance of adult returns because the overwintering life stage constrains the number of smolts that can be produced from a watershed (Solazzi et al. 2000; Beechie et al. 2001). Empirical spawner-recruit relationships also suggest that populations may be limited by both habitat capacity and survival, and that in some cases increasing survival at certain life stages will not increase spawner abundance if habitat capacity is not correspondingly increased (Walters et al. 2013; Bal et al. 2018; Hinrichsen and Paulsen 2020).

Expectation 2. We are restoring enough of the right kinds of habitat

A key expectation in the design of restoration work implemented within IMWs is that we are restoring the scarcest or most impaired habitats, and at the correct scale. This expectation is often based on models or expert opinion identifying critical limiting factors in need of improvement that have not yet been locally tested. Circumstances in a stream of interest may also not match model or expert opinion assumptions and requirements, due to several reasons, including but not limited to a shift in baseline habitat conditions since limiting factors were initially determined (Thurow et al. 2020). Our current definition of “acceptable” or “functional” environmental and habitat conditions does not fully reflect conditions that support healthy, resilient populations

(Thurow et al. 2020; Wohl et al. 2021; McMillan et al. 2022). For example, river-wetland corridors historically connected channels, wetlands, ponds, and lakes across floodplains, but their presence has been so diminished that the general public and even many river managers are unaware of their former pervasiveness (Wohl et al. 2021; Powers et al. 2022). As a result, current habitat restoration targets tend to be well below habitat availability and diversity levels that historically supported large salmon populations (Beechie et al. 2010; Beechie et al. 2013). Furthermore, there is the expectation that a sufficient portion of lost or degraded habitat can be restored to make a difference in targeted population response. This seems like a logical expectation given the multi-millions of dollars spent annually on recovery efforts for Pacific salmon (Roni et al. 2002), yet the scale of restoration is quite small compared to the scope and extent of existing habitat degradation (Roni et al. 2010). The amount of stream and watershed restoration needed to generate significant population response has been suggested to range between 20% of a watershed's drainage network to almost the entire watershed in order to see a response that can be statistically demonstrated (Scheuerell et al. 2006; Roni et al. 2010; Jorgensen et al. 2021). Additionally, expressing the extent of habitat restoration as a localized metric, such as miles of stream directly affected by a restoration action, ignores the broader need of restoring watershed processes that sustain productive aquatic habitats over time.

Restoring natural processes conceptually provides the greatest long-term benefits to aquatic communities (Sedell and Beschta 1991; Beechie et al. 2010). Focusing on natural processes allows for the dynamic nature of ecosystems to be expressed, which can result in multiple habitat states. Natural watershed processes and fish population resilience are impaired due to watershed degradation and can be reduced more so over time by climate change, invasive species, and greater exploitation of natural resources (Munsch et al. 2022). We acknowledge that treating habitat degradation symptoms, such as in-stream wood loss, by adding instream wood to streams may be initially important to help accelerate restoration of impaired habitat conditions. Such additions may require multiple treatments over decades due to degraded riparian conditions, as was the case in Deep Creek where 23 years of wood additions resulted in aquatic habitat recovery (Pess et al. 2023). However, this is not a long-term solution because habitat restoration is not the final step; rather, restoration of natural processes and the allowance for various habitat outcomes to take hold is the best way to recover watersheds and populations (Bellmore et al. 2019).

Expectation 3. Natural variation will not obscure responses to restoration

Anadromous fish populations vary over space and time, reflecting the influences of the highly dynamic marine, nearshore, and freshwater environments in which they evolved and presently occupy (Waples et al. 2008). Several studies indicate that abundance changes related to restoration can be observable (i.e., restoration signal exceeds environmental noise) when the scale of restoration is large enough and restoration actions address important habitat factors that limit fish production (Copeland et al. 2021). Modeling scenarios suggest that when habitat restoration is sufficient to increase average abundance by at least 25%, the effect of restoration can be statistically detectable for certain salmonid species (Roni et al. 2010), assuming significant shifts in environmental variability caused by climate change or other major environmental drivers do not occur. Restoring habitat connectivity by migration barrier removal and floodplain reconnection are common restoration actions that have resulted in positive salmon responses at multiple life stages, including returning adults (Pess et al. 2014; Ogston et al. 2015; Copeland et al. 2021). Restoring access to historically accessible spawning and rearing habitats does appear to be effective in producing a restoration signal that can be detected over environmental noise. Removing large barriers (including dams) can expand the distribution of salmon populations by over 50% of a watershed, and can increase adult salmon population abundance by 100% to 400% (Pess et al. 2014). Instream flow enhancements and fish screen diversions can also increase available habitat and salmon productivity (Copeland et al. 2021). Documentation of salmon population responses to actions affecting small areas of a watershed has been much more difficult.

Expectation 4. Responses to restoration can be measured within a short time period

Implementing restoration actions at a watershed scale is both time consuming and expensive (Roni et al. 2005). Restoration activities often take many years to complete, and the response may take many years to detect. The time required to detect a population response depends primarily on the response parameters selected. Responses to be measured (e.g., population metrics, physical habitats, water quality conditions, aquatic food webs) vary with the type of restoration action (Roni and Beechie 2013), and the time required to detect a response may vary by response parameter. The time required to quantify a response to watershed restoration actions is influenced by whether the focus is on quantifying juveniles or spawning adults. For Pacific salmonids, field studies suggest a minimum of 3 years up to approximately 35 years to detect abundance changes with reasonable certainty (Solazzi et al. 2000; McHenry and Pess 2008; White et al. 2011; Pess et al. 2014; Bouwes et al. 2016; Brenkman et al. 2019). Oregon coastal Coho Salmon and steelhead were estimated to require 10 to 35 years of monitoring in order to document a two to three-fold increase in parr and smolt production after habitat improvements (Solazzi et al. 2000). Power analysis completed before Washington’s Elwha River dam removal suggested that documenting a two-fold increase in the number of returning adult Chinook Salmon would require approximately 20 years of monitoring (about 4 to 5 generations) before a significant change could be detected (McHenry and Pess 2008). Elsewhere, salmon reintroduction after barrier removal and the creation of new habitats has resulted in a one to four-fold increase in population abundance within 10 to 30 years post-restorative action (Pess et al. 2014). In-stream habitat improvement actions such as wood placement, particularly in smaller streams (<15 m bankfull width), can lead to increases in adult biomass within five years with benefits lasting up to 20 years post-restoration (White et al. 2011). However, Bilby et al. (2022) found that many Pacific Northwest IMWs have been unable to document significant habitat and target species improvements following wood additions, although these studies have not been completed. Nearly all restoration projects have addressed physical habitats and channel-forming processes. Very few have dealt with restoring productive food webs that support fish growth and physiological health, and we are not aware of any studies that have estimated the time required to restore freshwater trophic regimes of Pacific salmon.

Lessons from IMW Study Design

We have learned much about conducting IMW studies involving habitat improvement actions at the scale of entire watersheds, as well as designing and implementing large-scale restoration response research. These lessons can be useful to others considering future IMW investigations.

1. IMWs should include assessments of which restoration actions are most beneficial and how much and what types of restoration are needed to see a response

An important aspect of restoration planning in the context of IMWs is the use of analyses of current and potential habitat conditions, salmon life-cycle models, and salmon limiting factors analysis (Beechie et al. 1994, 2015; Jorgensen et al. 2021). These analyses lead to testable hypotheses concerning which types of restoration actions should be the focus of stream and watershed restoration so salmon population responses can be potentially detected through watershed-scale monitoring (Flitcroft et al. 2016). Such analyses should be completed prior to implementing restoration actions in IMWs (Beechie et al. 2010) and will form the basis for long-term hypothesis testing.

The expectation that we are restoring enough of the impaired habitats is rarely evaluated rigorously prior to implementing restoration actions. Restoration planning approaches are available for assessing landscape change (Bartz et al. 2006; Roni et al. 2017; Beechie et al. 2021), and for using life-cycle models or limiting factors analysis to identify the types, locations, and scale of habitat restoration actions that are needed to produce a desired population response (Scheuerell et al. 2006; Jorgensen et al. 2021). Such analyses may highlight that commonly implemented actions are unlikely to produce a large salmon population response because they do not address the most important and widespread habitat problems (Jorgensen et al. 2021), and that a shift in focus is needed. Ultimately, IMWs, and other less well monitored restoration sites, if designed properly, provide the means to test whether habitat conditions in watersheds have been restored successfully; they are not designed to test an *a priori* assumption that restoration has achieved management objectives. Lessons learned from IMWs should feed directly into an adaptive management process (Bouwes et al. 2016).

IMW studies should include assessments of how extensive restoration treatments need to be to have measurable effects on target fish populations (Roni et al. 2010). Larger watersheds typically have more extensive degraded areas that need to be addressed though stream and watershed restoration actions. Downstream areas of large watersheds can also be more impaired than those within small watersheds due to cumulative effects of multiple stressors, versus a single type of habitat degradation. Greater funding and stakeholder coordination is typically needed to address stream habitat impairments within large watersheds.

2. IMWs are designed to maximize what we can learn from habitat interventions, but they are not classical experiments

Monitoring design should consider both the underlying assumptions of the study and how the study design affects the ability to detect a restoration signal. One consideration is that IMWs should include the spatially explicit monitoring of life stages of the species of interest. Expanded utilization of suitable habitats through barrier removal can lead to increases in fish growth and survival, or allow for a greater number of life history types, all of which can lead to greater abundance and population resilience (Bisson et al. 2009). However, IMW response metrics such as fish abundance can be highly variable in space and time at the watershed scale (Roni and Quinn 2001; Downes et al. 2002; Liermann and Roni 2008) and investigators must factor this variability into study designs and interpretation of results.

To detect a treatment effect, investigators can implement a variety of monitoring designs to measure response variables and their spatial and temporal variation (Underwood 1994; Roni et al. 2005; Loughin et al. 2021). These designs typically include monitoring within treatment and control sites. However, an ideal, balanced, BACI experimental design with precisely replicated treatments and controls is impractical in a broad landscape setting. This is not to imply that careful attention should not be given to setting up a study where management actions can be evaluated, but rather to accept that implementing such studies with normal operating constraints in highly variable environments is likely to prove diffcult (Bennett et al. 2016).

One of the major differences between a classical experiment and watershed-scale ecological experiment is the interpretation of control sites. In laboratory studies, the ability to create a control that is identical to the treatment (except for the treatment) is an essential part of statistical design; however, at the scale of a watershed, neither identical replicates nor rigid environmental controls are feasible. Temporal variability controls power in BACI designs and synchrony between restoration and control watersheds may do little to increase power in field conditions (Rogers et al. 2022). Moreover, where conditions in treated and control watersheds do not follow identical trends prior to treatment application, because of natural disturbances, hatcheries, harvest, and land-use activities that occur differentially within treatment and control watersheds, the use of control sites in a BACI design may actually reduce statistical power (Roni et al. 2005). Researchers must adapt the strengths of designed experiments to the realities of control sites and select control watersheds as close as possible and as similar as possible to experimental treatment watersheds.

One reality that IMW studies have demonstrated is that both natural and anthropogenic events contribute to the difficulty of detecting treatment effects. Unanticipated events such as severe floods, fires, or droughts cannot easily be factored into the original study design; however, such changes are common in multi-year, watershed-scale studies and should be accepted as an inevitable part of the research. In addition, a lack of sufficient spawning adults to repopulate restored stream habitat can prolong or prevent the demonstration of treatment effects. The idea that "if you build it, they will come" may not be immediately realized, and in some cases restoration sites may be invaded by non-target species. On the other hand, extreme natural and anthropogenic events can provide unique opportunities for learning, and taking advantage of these rare opportunities by investigating the effects of the event may add to the overall utility of the IMW project.

3. Natural variability can make it difficult to detect responses to experimental treatments, requiring adjustments to typical study designs

Temporal variability decreases statistical power, making it difficult to detect significant treatment effects and thereby necessitating either a larger sample size or a longer measurement window, or both. For example, data from four streams in coastal Oregon showed that it might take more than 70 years to detect a doubling of Coho Salmon smolt production in response to habitat restoration using a BACI design (Roni et al. 2003). Having a large sample size and randomizing treatments across study units can improve statistical power and reduce the potential for bias (Liermann and Roni 2008), but imposing these constraints on IMW study designs can be impractical. Recently, Rogers et al. (2022) have suggested that causal relationships from restoration actions to salmonid population metrics may be better drawn from designs such as Extensive Post-Treatment (EPT) or multiple BACI (mBACI) where multiple reach-scale, treatment-control pairs are distributed within a drainage basin or across a region.

In an environment where decision makers do not have the luxury of multi-decade time horizons for evaluating policy choices, investigators are usually constrained to carry out the study in less time than is necessary to properly implement a classical design that could fully accommodate natural variation. A common tendency among scientists is to intensively monitor a small set of study sites for longer periods of time in order to truly understand ecological patterns at a particular location (Bormann and Likens 2012). However, statistical gains can be made by increasing the sample size, allowing the larger number of observations to absorb the natural variability so that trends across space and time can be better quantified (Liermann and Roni 2008). Staircase designs (Walters et al. 1988), in which treatments are implemented over a series of years in stepwise fashion, are intended to separate the effects of environmental variation over time from treatment effects, and thus control for time-treatment interactions. Simulations performed on various study designs for IMWs found that a staircase design, where treatments were temporally staggered in one treatment section in each stream had the highest power and best precision, particularly when the variance in juvenile fish densities were high (Loughin et al. 2021). Conversely, a tradition BACI design performed the worst, with intermediate performance using a combination BACI and staircase design (Loughin et al. 2021). Combined BACI and staircase designs tend to be more complicated and expensive to carry out at large spatial scales. The specific restoration questions being asked will determine the most appropriate study design, given natural variability.

4. Statistically significant changes in abundance may not reveal the full range of restoration benefits

While a commendable goal, obtaining statistically significant changes in juvenile abundance from restoration efforts is difficult, particularly if post-treatment monitoring is limited to a few years. Differences between the pre- and post-restoration means are often large but not statistically significant. For example, Reeves et al. (1997) found that the mean number of steelhead smolts leaving Fish Creek, Oregon, increased 27.7% following restoration and mean number of age 1+ steelhead increased 11.7%. However, neither change was statistically significant because of the large variation around the long-term means.

Responses to restoration efforts, however, may be ecologically important even if they do not achieve statistically significant thresholds. Increased juvenile growth and outmigrant size is a seldom acknowledged goal of restoration, but it can be a key to population viability (Copeland and Venditti 2009). In Fish Creek, Oregon, the size of juvenile steelhead increased with restoration, 4.1% and 3.2%, respectively (Reeves et al. 1997), but the increase was significant for age 1+ fish and not for age 2+ smolts. However, improved growth can be an important response to restoration because larger fish generally have higher marine survival rates (Brakensiek and Hankin 2007), which is particularly critical in times of poor ocean conditions. Expression of new life-history patterns as a result of restoration efforts (Bottom et al. 2005) is another example of critical ecological benefit that may not be expressed in abundance, but yet be beneficial to a population by providing greater life history diversity.

5. Scientists and managers should work together to design, conduct, and interpret results of IMW studies

Scientists and restoration managers together should establish realistic expectations for what can be done to maximize learning opportunities where a rigid control of factors other than the variables of interest cannot be achieved. For managers, this may mean forgoing some operational flexibility in terms of restoration implementation to maintain as much treatment consistency as possible across study locations. For scientists, this may mean having to make concessions in the types of treatments and the location and timing at which they are applied. Both managers and scientists should also collectively establish realistic expectations of results relative to the questions being asked. It is possible that over the course of the study there may be strong pressure to conduct restoration in control watersheds. While such activities are likely to confound results, scientists should realize that the ultimate decision on watershed-scale habitat restoration resides with policy makers and be prepared to factor unanticipated interventions in control sites into the final analysis of results.

6. Investigators should implement a design and stick with it until the important questions are resolved. If variation of the parameters of interest proves too great and goes beyond what was planned, then it may be time to stop

IMWs are typically set up as large-scale, long-term studies because restoration activities, even just one type, can require years to decades to fully implement and mature (Pess et al. 2023). It is unreasonable to assume that stream and watershed restoration actions can reverse in a few years what took a much longer time period to degrade (Allan 2004). Even for simple restoration actions that re-open large amounts of habitat, fish responses can take many years to fully measure (Pess et al. 2014). For more complex situations involving multiple restoration actions, biophysical processes need to function properly over long enough time periods to sustain the desired habitat changes. It is important for all stakeholders to understand that stream and watershed restoration effects may not be fully expressed immediately, that the indirect effects of restoration often require time to sort out, and that there is a need to commit to supporting monitoring for extended periods (Diefenderfer et al. 2021).

It is also important to avoid introducing fundamentally different types of restoration actions during the timeframe of an existing IMW design (e.g., supplementing wild fish with fish of hatchery origin). This can confound study results. Conversely, it is important to recognize that if results of monitoring prove to be extremely variable, there may be no compelling reason to continue due to extreme variation. It may take several years or one exceptionally large disturbance to reach this conclusion, but there is little to be gained by continuing research that cannot lead to new insights, even if treatment consistency is maintained.

7. It may be advantageous to employ novel response metrics during an IMW study, and when surprises occur, to be flexible enough to monitor their effects in order to maximize learning opportunities

It may become apparent after a study has been initiated that adding a new metric to the suite of response variables in the monitoring plan can yield important information (Tonra et al. 2015, 2016). Even if the metric or method is relatively untested in the context of the IMW study questions, the benefits of incorporating something novel with the potential to shed new light on ecological processes that control system response may outweigh the risks of ignoring it. Conversely, if a metric does not provide useful information after a reasonable trial period, it can be dropped from the effort. A new metric might not help answer the original questions but instead may contribute information of a different value. Addition of a new metric to the suite of response variables does not mean altering the initial study design.

In summary, IMWs can provide valuable information at the watershed scale because they allow us to monitor changes at scales relevant to breeding populations. This is important to mangers and funding entities who want to know if the actions and investments are improving fish species of interest. However, it is critical to understand that IMWs are complex, large-scale, long-term studies that can take decades to demonstrate habitat improvement effects at the population level, and therefore they require continued commitment from stakeholders. If IMWs are implemented and thoughtfully managed, they can provide recovery insights that cannot be captured with other methods.

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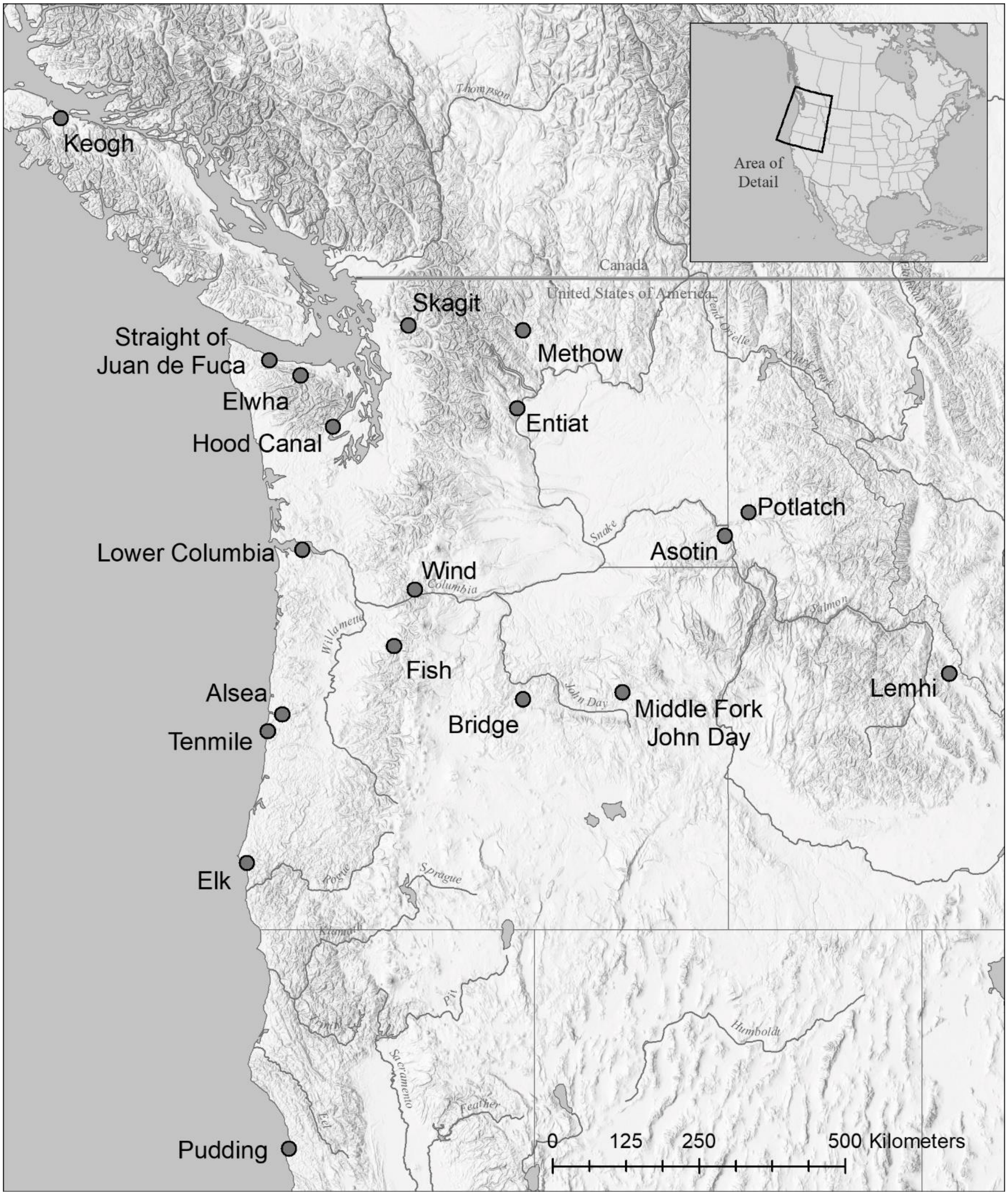
Figure and legend

Figure 1. Location of currently active intensively monitored watersheds in the Pacific Northwest (redrawn with permission from Bennett et al. 2016).


Area of Detail
Canada
United States of America
Keogh
Straight of Juan de Fuca
Elwha
Hood Canal
Skagit
Methow
Entiat
Potlatch
Asotin
Lower Columbia
Wind
Fish
Alsea
Tenmile
Bridge
Middle Fork John Day
Lemhi
Elk
Pudding
Thompson
Fraser
Pend Oreille
Clark Fork
Snake
Columbia
Willamette
John Day
Salmon
Rogue
Sprague
Klamath
Pit
Trinity
Sacramento
Eel
Feather
Humboldt
0
125
250
500 Kilometers