Detecting persistent change in the habitat of salmon-bearing streams in the Pacific Northwest

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Abstract: In the northwestern United States, there is considerable interest in the recovery of Pacific salmon (*Oncorhynchus* spp.) populations listed as threatened or endangered. A critical component of any salmon recovery effort is the improvement of stream habitat that supports various life stages. Two factors in concert control our ability to detect consistent change in habitat conditions that could result from significant expenditures on habitat improvement: the magnitude of spatial and temporal variation and the design of the monitoring network. We summarize the important components of variation that affect trend detection and explain how well-designed networks of 30–50 sites monitored consistently over years can detect underlying changes of 1–2% per year in a variety of key habitat characteristics within 10–20 years, or sooner, if such trends are present. We emphasize the importance of the duration of surveys for trend detection sensitivity because the power to detect trends improves substantially with the passage of years.

Résumé : On s'intéresse beaucoup, dans le nord-ouest des États-Unis, au rétablissement des populations de saumons du Pacifique (*Oncorhynchus* spp.) considérées comme menacées ou en voie de disparition. L'amélioration des habitats des cours d'eau qui abritent les différents stades du cycle des saumons est une composante essentielle de ce rétablissement. Deux facteurs associés, soit l'importance des variations spatiales et temporelles et la planification du réseau de surveillance, déterminent la capacité de détecter les changements stables de conditions de l'habitat résultant de dépenses importantes consenties pour son amélioration. Nous présentons une synthèse des principales variations qui affectent la détection des tendances, ainsi qu'une démonstration que des réseaux bien planifiés de 30–50 sites suivis constamment au cours des ans peuvent déceler des tendances sous-jacentes de 1–2 % par année pour une variété de caractéristiques fondamentales de l'habitat sur une période de 10–20 ans ou moins, lorsque de telles tendances existent. Nous insistons sur l'importance de la durée des inventaires pour la sensibilité des détections de tendances parce que la capacité de déceler les tendances s'améliore au cours des années.

[Traduit par la Rédaction]

Introduction

The decline of wild Pacific salmon (*Oncorhynchus* spp.) in riverine–riparian ecosystems of the Pacific Northwest has led to considerable scientific, political, social, philosophical, and financial efforts to identify causes for the decline and find solutions (Huntington et al. 1996; Nehlsen 1997; Lackey 2000). The varied and complex causes of the decline tend to fall into several broad categories: freshwater and estuarine habitat degradation, commercial and recreational harvest, hydropower (dams) and water diversion from stream channels, oceanic conditions, hatcheries, and biological interactions such as predation and competition from introduced species (National Research Council 1996; Committee on Environment and Natural Resources 2000; Federal Caucus 2000). These factors affect all life stages to varying degrees and, in aggregate, affect salmonid populations at regional scales (e.g., bioregions, provinces, evolutionarily significant units) over time scales of a decade and longer. Therefore, solutions addressing the multiple causes of salmonid decline must also vary, both in spatial and temporal scales and in scientific and sociopolitical complexity (Federal Caucus 2000; Lackey 2000).

The degradation and potential recovery of freshwater riparian and stream channel habitat is an important part of salmon recovery. Human settlement along stream and river corridors during the past 150 years has altered the fundamental processes that created the habitat conditions under which salmonid populations have evolved and adapted over centuries (Bisson et al. 1992; Beechie and Bolton 1999; Naiman et al. 2000). These fundamental processes include the supply of sediment, wood, and nutrients to channels, the flow regime, connections to floodplains, and riparian vegetative cover and composition. Habitat conditions altered by human-induced changes to fundamental processes include the longitudinal frequency and depth

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of pools, the composition of stream bed substrate, riparian vegetative cover, the complexity of channel habitat, and floodplain connectivity.

In response to these changes, a variety of plans and approaches are being developed and implemented to improve freshwater habitat conditions thought to be most important to salmonid survival (Schmitten et al. 1995; Tuchmann et al. 1996; Independent Scientific Group 1999). Local-scale activities are underway, such as adding habitat structure to stream reaches (wood placement, streamside stabilization, native riparian vegetation planting) and modifying road building and management to minimize excessive sediment supply to streams (proper culvert construction, retiring of inactive roadbeds, construction of new roads on stable land types). Broader regional-scale principles and procedures are also being implemented, such as conducting watershed analysis to guide watershed restoration. Federal and state policies have been embodied in the Northwest Forest Plan (Tuchmann et al. 1996), in the Oregon Plan for Salmon and Watersheds (Nicholas 1997), and in the accumulation of legal decisions on lawsuits aimed at ensuring compliance with existing mandates promulgated by the Clean Water Act or the Endangered Species Act.

A key factor in determining the success of these combined activities and policies is a sound monitoring program that tracks changes over time frames appropriate to the spatial and temporal scales of expected responses. Given that habitat degradation has probably been occurring gradually for decades and longer, and that recovery activities will not restore habitat within a short time frame at regional scales, a monitoring plan that tracks habitat features at regional spatial scales over decades is of primary importance. A step toward designing and implementing such a monitoring program is to evaluate trend detection capability. What trends are we likely to detect at what cost? An issue sometimes raised is that the features of interest are so spatially and temporally variable that only the strongest of trends can be detected. As we show, however, a carefully designed monitoring network can quantify and manage spatial and temporal variation and detect gradual changes in key indicators.

During the past decade, we conducted a series of regional monitoring surveys in small, perennial streams in the size range important for spawning and rearing of Pacific salmon, measuring many significant attributes of stream and riparian habitat. The survey designs allowed us to calculate components of variation important in detecting regional trends (Urquhart et al. 1998; Larsen et al. 2001). In this article, we describe the key components of variation that affect regional trend detection, summarize our estimates of these components for several key physical habitat indicators, and demonstrate the trend detection sensitivity of a regional network of sites (its power to detect trends of specified magnitudes).

Materials and methods

Trend detection

The ability of a monitoring program to detect trends is sensitive to spatial and temporal variation in the target indicators as well as to design choices for a network of sites and the timing and frequency of sampling (Urquhart et al. 1998; Urquhart and Kincaid 1999; Larsen et al. 2001). Restoration of habitat is expected to produce conditions that vary spatially and temporally and that could mimic conditions to which salmonids have adapted (Reeves et al. 1995; Abbe and Montgomery 1996; Bisson et al. 1997). To evaluate the effects of spatial and temporal variation, we have focused on four major components of variation whose management is useful for evaluating and controlling trend detection power: site, year, interaction, and residual variation (Table 1).

We define trend as a persistent unidirectional (positive or negative) change across years, as elaborated in Urquhart et al. (1998). Trend can be with or without pattern. In either case, a trend contains an underlying linear component. Our evaluation of trend detection capability relies on the detection of this underlying linear component, which will be present with any complex, consistent pattern of change (Urquhart et al. 1998). More complex change and trend detection methods might detect trends sooner, and with greater power, than we suggest here. We do not know what the pattern will be ahead of time, but once it unfolds (if present), trend detection techniques that take the pattern into account are likely to indicate trend sooner than a simple linear approximation. Hence, our evaluation can be considered a conservative evaluation of trend detection capability (power to detect a specified trend if such a trend is present) (Gerrodette 1987; Peterman 1990; Gibbs et al. 1998). We hypothesize that the underlying linear component will be different from zero when a trend is present. Trend detection sensitivity, therefore, evaluates the likelihood of distinguishing whether a slope (change per year) of a specified magnitude in the mean value of a habitat characteristic (e.g., pool depth) across a network of streams differs from zero.

Stream surveys

We base our evaluation on six surveys that included 392 stream reaches and 200 repeat visits. These surveys were conducted in Oregon and Washington from 1993 to 1999. Most were from 1 to 3 years in duration, but one survey lasted 6 years (Table 2). These surveys targeted wadeable perennial streams occupied by diverse salmon species and life stages. A team of two persons measured a comprehensive set of habitat characteristics in about 3 h with simple measuring devices, such as tape measures, clinometers, surveying rods, and visual estimation. Stream reach length ranged from 150 m to 1 km; catchment areas ranged from 0.1 to 150 km^2 (Kaufmann and Robison 1998; Kaufmann et al. 1999).

For each survey, a region of interest was specified (e.g., the stream network in the coastal province of Oregon and Washington or the stream network in the Central Cascades of Oregon). Then, a set of stream sites (specified by the desired sample size) was selected for field monitoring from the network, as represented on 1 : 100 000-scale U.S. Geological Survey digital stream traces. The site selection procedure uses a probability survey design similar to a simple random sample, with the exception that it guarantees that any selected sample has the same spatial distribution as the stream spatial distribution (Stevens and Olsen 1999). Because of the randomized selection process, measurements made at the sampled locations can be used to infer conditions within the entire specified network of interest. Each design was constructed to facilitate estimation of the applicable components of variation (specified in Table 1). Field crews sampled the

Table 1. Summary of the four components of variation important for evaluating regional trend detection power (Urquhart et al. 1998; Larsen et al. 2001).

Component of variation	Description
Site	Persistent differences among stream reaches across a region are expressed through site-to-site variation. For example, stream size or gradient differs across the landscape. Some stream channels are constrained by V-shaped valleys and are regularly scoured to bedrock; other channels are contained in broad alluvial valleys and have high alluvial loads. Similarly, some stream channels are inherently more capable of supporting more deep pools than others, or more large wood. These differences among stream reaches in a region are captured by site-to-site variation
Year	The synchronous or coherent yearly variation among all sites in a network that might be influenced by regional-scale forces such as climate, broad-scale disturbances, or ocean conditions. An example is the synchronous variation in stream flows that are higher than normal at all sites during a wet year but lower than normal at all sites during a dry year
Interaction	The independent, desynchronized yearly variation among all sites in a network, subject to local-scale influences. An example is the yearly variation in the amount of wood or fine sediments in stream channels. The supply of wood or sediments might be quite patchy spatially and variable temporally such that some reaches receive high amounts in particular years but lower amounts in other years, whereas the reverse might be true for other reaches
Residual	Residual variance captures the remaining variation. It consists primarily of the short-term variation during the temporal window when measurements are made, measurement error, and team-to-team differences in applying the same field protocol

Table 2. Summary of the regional surveys on which the variance analyses are based.

Region	No. of sites	No. of within-year revisits	No. of between-year revisits	Years covered by survey
Willamette Valley/Cascades (Oregon)	46	22	51	1993–1997
Oregon–Washington Coastal Ecoregion	139	35	59	1994–1996
Upper Deschutes (Oregon)	54	12	1	1997–1998
Upper Chehalis (Washington)	27	5	0	1997
Tillamook/Kilchis (Oregon)	53	6	1	1998–1999
Oregon Coastal Ecoregion	73	8	0	1998
Total	392	88	112	1993–1999

selected stream sites during a low-flow summer index window, generally between July and mid-September.

Habitat attributes

This evaluation focuses on several habitat characteristics (*i*) commonly agreed upon as important to salmon and other aquatic species, (*ii*) frequently targeted in restoration activities, and (*iii*) expected to respond to improved management practices (MacDonald et al. 1991; Committee on Environment and Natural Resources 2000; Bauer and Ralph 2001). Although numerous other stream channel features are important to salmon and are often incorporated into monitoring programs, we chose these as illustrative of patterns of variation and of the potential for detecting subtle, decadal-scale trends. Our selection of habitat attributes does not imply that salmon abundances would necessarily increase, should positive trends be present. The approach is applicable to other streams in other regions. Our selected habitat characteristics include pools, riparian canopy cover, fine sediments, and large wood.

Pools

Pools are quiet waters of greater than average stream depth distributed along the longitudinal profile of a stream channel. Pools serve a variety of functions for many salmon species and life stages, particularly for juveniles (Beechie and Sibley 1997; McIntosh et al. 2000). It is thought that both the frequency of pools (e.g., number of pools per unit length of stream channel) and the average pool depth have decreased over the past century as a result of broad-scale human activities (Beechie and Sibley 1997; McIntosh et al. 2000; Collins et al. 2002). Regional increases in average pool depth and pool frequency are expected as a response to numerous local- and regional-scale management actions. Our surveys estimate residual depth (Lisle 1987; Robison and Kaufmann 1994; Wood-Smith and Buffington 1996), defined as the depth of water that would remain if stream flow ceased; this measure of pools removes the effect of discharge variation on the definition and characterization of pools.

Riparian canopy cover

Shading of sunlight by the riparian canopy cover maintains the cool stream temperatures necessary for salmon reproduction and growth (Rutherford et al. 1997; Mitchell 1999; Bartholow 2000). Riparian cover also serves as a source of small and large (especially large wood) particulate organic matter, which is important to the maintenance of channel structural complexity and metabolism (Gregory et al. 1991; Naiman et al. 2000).

Streamside activities, such as farming, silviculture, and construction, are responsible for substantial reduction in riparian canopy cover. We measure riparian cover as the proportion of a convex hemispherical densiometer on which the reflection of riparian vegetation is visible (Kaufmann and Robison 1998; Kaufmann et al. 1999).

Fine sediment

An excess of fine sediment (sediment particles of <2 mm) in stream channels fills spaces in larger sized substrates, thereby eliminating critical habitat and reducing the flow of oxygen to invertebrates and to developing salmon eggs and juveniles (Kondolf 2000). Much current management activity attempts to reduce or eliminate excess fine sediment in stream channels through proper road construction and maintenance as well as prevention of timber harvest in riparian areas or on slopes particularly sensitive to mass wasting. By means of systematic pebble count procedures (Wolman 1954), we measure fine sediment as the proportion of sand, silt, and finer substrate particles estimated to be <2 mm in diameter (Kaufmann and Robison 1998; Kaufmann et al. 1999).

Large wood

Research during the past 20 years has revealed the ecological importance of large wood (generally defined as pieces >10 cm in diameter and 1.5 m long) in stream channels. It creates pools and cover for aquatic organisms, stabilizes stream banks, and fosters habitat diversity (Harmon et al. 1986; Maser and Sedell 1994; Ralph et al. 1994). Until the 1970s, stream channels were actively cleared of large wood. As a result of subsequent research, management activities now encourage the replenishment of wood in stream channels through a variety of actions. Wood is placed directly into stream channels, the removal of large wood is prevented, and riparian corridors are protected to promote the regrowth of natural riparian vegetation that regenerates natural supplies of wood to channels. However, stream cleaning is still widespread in urban and agricultural settings. Our protocols count the number and sizes of pieces of large wood and express results in terms of the volume of wood per unit length of channel (Kaufmann and Robison 1998; Kaufmann et al. 1999).

Analytical methods

For each of the four habitat characteristics, we estimated the magnitude of the components of variation for each survey separately; we also made estimates from all surveys combined. We use a linear model of the following form as a framework for identifying and calculating the components of variation (Table 1): $X_{ijk} = \mu + \mathrm{St}_i + Y_j + \mathrm{St}Y_{ij} + R_{ijk}$, where X_{ijk} is the response for the kth visit at stream site i during year j, μ is the overall mean, St_i is the random effect due to stream site i, Y_j is the random effect due to year j, $\mathrm{St}Y_{ij}$ is the random effect due to the interaction of stream site i and year j, and R_{ijk} is the random effect due to residual variation for the kth visit at stream site i during year j. In this model, subscript i ranges from 1 to l (the number of stream sites surveyed), subscript j ranges from 1 to t (the number of years of data), and subscript k ranges from 1 to r_{ij} (the number of visits during year j at stream site i). The components of variation are defined as follows: $\mathrm{Var}(\mathrm{St}_i) = \sigma^2_{\mathrm{Stream}}$ for all i, $\mathrm{Var}(Y_j) = \sigma^2_{\mathrm{Year}}$ for all j, $\mathrm{Var}(\mathrm{St}Y_{ij}) = \sigma^2_{\mathrm{Interaction}}$ for all i and j, and $\mathrm{Var}(R_{ijk}) = \sigma^2_{\mathrm{Residual}}$ for all i, j, and k. Total variance then consists of the sum of the four components: site variance ($\sigma^2_{\mathrm{Stream}}$), year variance ($\sigma^2_{\mathrm{Year}}$), interaction variance ($\sigma^2_{\mathrm{Interaction}}$), and residual variance ($\sigma^2_{\mathrm{Residual}}$).

In multiple-site surveys, in which a network of sites is monitored consistently over time, the components of variation are captured by the attribute's time series. If the surveys are properly designed, the data obtained from multiyear monitoring can be used to estimate the magnitude of each of these components of variation. The sum of squares in an analysis of variance model can be partitioned into each of the components of variation and converted to mean squares. Mean squares and sample allocation are used to estimate variances as follows:

$$s^2_{\mathrm{Total}} = s^2_{\mathrm{Stream}} + s^2_{\mathrm{Year}} + s^2_{\mathrm{Interaction}} + s^2_{\mathrm{Residual}}$$

$$s^2_{\mathrm{Residual}} = \mathrm{MS}_{\mathrm{Residual}}$$

$$s^2_{\mathrm{Stream}} = (\mathrm{MS}_{\mathrm{Stream}} - \mathrm{MS}_{\mathrm{Interaction}}) / N_{\mathrm{Year}}N_{\mathrm{Visit}}$$

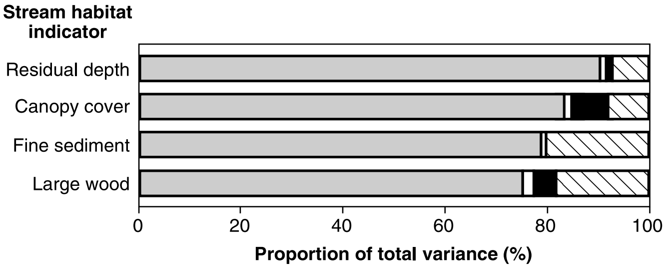
$$s^2_{\mathrm{Year}} = (\mathrm{MS}_{\mathrm{Year}} - \mathrm{MS}_{\mathrm{Interaction}}) / N_{\mathrm{Stream}}N_{\mathrm{Visit}}$$

$$s^2_{\mathrm{Interaction}} = (\mathrm{MS}_{\mathrm{Interaction}} - \mathrm{MS}_{\mathrm{Residual}}) / N_{\mathrm{Visit}}$$

The estimated components of variation (s^2) and mean squares (MS) are descriptively subscripted. Sample sizes (N) are subscripted by number of stream sites, years, and visits to a stream within a year. These formulas assume a balanced design in a sites-by-years matrix, with revisits to all sites each year. Most standard statistical software packages provide routines for calculating the components of variation when balanced designs are used; sometimes these are called repeated measures designs. For unbalanced designs (in which not all sites are revisited within a year nor are all sites monitored each year), the same framework is used for estimating components of variation, but the calculations are more complicated. An alternative approach for estimating components of variation for unbalanced designs is to use estimation methodology based on maximum likelihood, which is available in many statistical programs (e.g., SAS and S-PLUS). Specifically, a variant of maximum likelihood estimation referenced as restricted maximum likelihood can produce components of variation estimates for any design.

Our evaluation of trend detection capability considers regional trend as the average across a set of site-specific trends. Consider a network of stream sites that has been monitored for years. At each stream site, the temporal trajectory across years can be evaluated for site-specific trend. The average value of this set of site-specific trends comprises regional trend. As noted earlier, any trend, patterned or not, has an underlying linear trend; it is this underlying linear component of the consistent trend that we hypothesize to be different from zero and on which we base trend detection capability. Trend detection sensitivity, therefore, evaluates whether the slope differs from zero and is based on an expansion of the usual linear regression model (e.g., Draper and Smith 1967; Urquhart et al. 1998; Larsen et al. 2001) as follows:

Fig. 1. Relative magnitude of the four components of variance for the key habitat attributes evaluated illustrating the dominance of the site component of variation and the relatively small magnitude of both the year and interaction components. Components of variation: site (shaded bars), year (open bars), interaction (solid bars), and residual (hatched bars).



$$\text{(1)} \qquad \mathrm{var(slope)} = \frac{\dfrac{\sigma^2_{\text{Stream}}}{N_{\text{Stream}}} + \sigma^2_{\text{Year}} + \dfrac{\sigma^2_{\text{Interaction}} + \dfrac{\sigma^2_{\text{Residual}}}{N_{\text{Visit}}}}{N_{\text{Stream}}}}{\sum (Y_t - \bar{Y})^2}$$

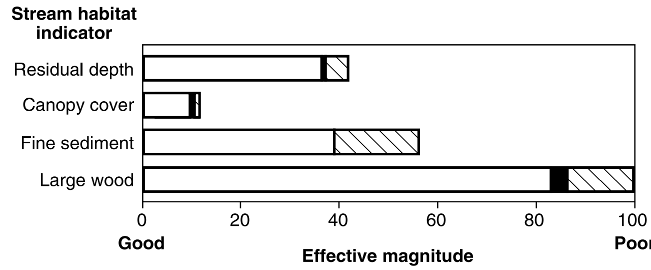
where σ^2 refers to variances as subscripted, N refers to the number of stream sites or the number of visits to stream sites in a particular year, and Y refers to years. Urquhart et al. (1998) provided the formal statistical basis for the trend detection model and power estimation that incorporates var(slope) along with justification for assumptions of approximate normality regarding the distribution of slope values. Exact computations of power depend on normality, but the comparative patterns that we describe hold up in the absence of normality.

The numerator of eq. 1 contains the components of variation described (Table 1) and illustrates how various design choices can affect trend detection capability; the denominator corresponds to the x-axis of a standard linear regression and is expressed in years because of the expected long time frame likely to be needed for trends in stream habitat to appear. In the numerator, the effect of the stream component of variance vanishes if revisits to stream sites are incorporated into the design. The interaction and residual variances are controlled by the number of sites in a network, but year variance is not. Furthermore, residual variance is controlled both by number of sites in the network and by number of revisits to sites within a year, but interaction variance is controlled only by the number of sites in the network. The effect of all components of variance on the ability to detect trends (var(slope)) is controlled by the duration (denominator) over which the survey network in monitored.

Results and discussion

Individual variance estimates from each survey did not differ in any substantial way from the grand estimation. The results summarize the relative magnitude of each of the four components, scaled to 100 so that comparisons can easily be made across habitat attributes measured on different scales and with different measurement units (Fig. 1). As might be expected because of the range of stream types, sizes, and local settings, most of the variation is associated with site-to-site

Fig. 2. The equation for the variance of a slope (eq. 1) can be viewed as a sum of three parts when stream sites are revisited across years: year, interaction, and residual. The relative effect of these parts on the variance of a slope is illustrated as a bar graph, rescaled to 100% for the most variable slope, for a design in which 50 stream sites are visited once annually. The effects of the interaction and residual components are minor compared with the dominant effect of the year component. Components of variation: year (open bars), interaction (solid bars), and residual (hatched bars).



differences among the streams. If unaccounted for in survey designs intended to detect regional trends, this site component of variation can substantially diminish sensitivity (Urquhart et al. 1998). However, if patterned revisits are incorporated across years, the effect of site-to-site differences is effectively eliminated in a manner analogous to experimental designs that use self-pairing.

The remaining components of variation affect sensitivity to trends to varying degrees, depending on design choices (Urquhart et al. 1998; Urquhart and Kincaid 1999; Larsen et al. 2001). The effect of the residual component of variation is sensitive to number of revisits to a site within a year (or within the seasonal temporal window during which the survey is conducted), but the effect of the interaction component is not. Both, however, are affected by the number of sites in the survey. As a result, it is generally better to add sites to a survey rather than revisit sites within the year, unless revisits to sites are much less costly than visits to new sites. The final component of variation, the year effect, cannot be managed by the same design choices as the other three components; regional trend detection is particularly sensitive to its magnitude (Urquhart et al. 1998; Urquhart and Kincaid 1999; Larsen et al. 2001). Rather, it is managed through measurement or evaluation of the factors controlling it (e.g., oceanic conditions, decadal weather patterns, regionally consistent stream flow patterns). If these controlling factors are identified and their effects on target variables quantified by modeling, then the "year effect" can be reduced.

To illustrate the interactions of these components and their effects on trend detection sensitivity, we examined their influences on detection of a 1–2% per year trend with a network of 50 sites. With a set of 50 sites visited every year, the effects of the interaction and residual components become minimal compared with the now undiminished year effect, whose relative influence is magnified (Fig. 2). When the year effect is substantial, increasing the number of sites in a network has little effect on trend detection.

Using the power of a statistical test to detect an outcome is increasingly being accepted as a means of evaluating sensitivity (Peterman 1990; Gibbs et al. 1998; Fox 2001). Power

Fig. 3. Power to detect 1% per year (broken lines) and 2% per year (solid lines) trends, with 80% power for each indicator, in the four habitat indicators (●, canopy cover; ▲, residual depth; no symbols, fine sediment; ■, large wood) with a monitoring network of 50 sites visited annually (α = 0.05).

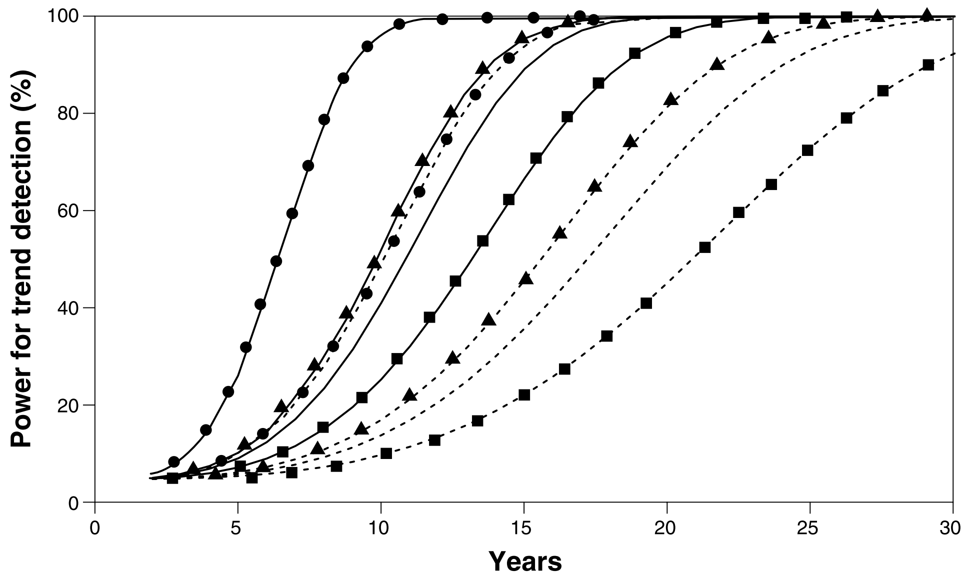


Table 3. Number of years to detect 1% per year and 2% per year trends in habitat attributes with 80% likelihood, if specified trends occur, as a function of number of monitoring sites sampled annually (α = 0.05). For comparison, sensitivity (in parentheses) is estimated for a design that uses a random set of sites monitored each year.

No. of sites	Residual depth	Canopy cover	Fine sediment	Large wood
1% per year				
10	22 (40)	15 (24)	28 (43)	32 (44)
20	21 (33)	14 (20)	24 (35)	29 (37)
30	20 (30)	14 (18)	23 (32)	28 (34)
40	20 (28)	13 (17)	22 (29)	27 (32)
50	20 (26)	13 (16)	21 (28)	27 (31)
2% per year				
10	14 (25)	10 (15)	18 (27)	20 (28)
20	13 (21)	9 (13)	15 (22)	18 (23)
30	13 (19)	9 (11)	14 (20)	17 (21)
40	13 (17)	8 (11)	14 (19)	17 (20)
50	12 (17)	8 (10)	13 (18)	17 (20)

describes the likelihood of detecting an outcome if that outcome occurs. For example, how likely are we to detect a 1–2% per year trend in our selected physical habitat characteristics, if such a trend occurs, as a function of the duration of a survey? A 1–2% per year trend is a rather small trend, amounting to a proportional change of about 15–30% of the initial value in 15 years. If trends of this magnitude indeed occur in these habitat attributes, the likelihood of detecting them is high within 10–20 years (80% and higher detection probability, 5% probability of incorrectly asserting a trend; Fig. 3). Power is clearly sensitive to the duration of the survey; a few additional years of monitoring increases sensitivity substantially, as shown by the steepness of the power curves.

Trend detection, based on these estimates of the variance components, is relatively insensitive to the number of sites in the survey (Table 3). We varied the number of sites from 10 to 50 and found, for some of the indicators, relatively little difference in the number of years to detect 1% and 2% per year trends. However, because surveys of this nature are intended to represent conditions at a regional scale, we suggest that at least 30–50 sites be used. Fewer sites might yield unacceptably high uncertainty for regional estimation. These results indicate a fairly consistent time frame within which subtle trends in stream habitat characteristics, if present, would be detectable. This consistency should be useful as a guide for communicating expectations for detecting underlying regional changes in the habitat of northwest streams in response to the array of current and potential management actions.

For contrast, we also illustrate trend detection sensitivity for less well designed surveys. For example, if the survey did not revisit sites across years, as in a design in which sites were selected at random each year, the site component of variation (divided by the number of sites in the survey) would be included as part of the numerator of eq. 1. The site component of variation is much larger than the sum of interaction and residual, accounting for 80–90% of the total variation (Fig. 1). The magnitude of site variance far outweighs the variation in interaction and residual variation among the various individual surveys. Hence, a survey design that includes random selection of sites each year can be considered a "worst-case" scenario for these indicators. With such worst-case designs, trend detection sensitivity could be substantially lower, particularly if relatively few sites are monitored, than in cases with sites revisited annually (as contrasted in Table 3). However, achieving the specified power for trend detection for some indicators is delayed only a few years, especially if 30–50 sites are used in the survey.

Although we use 50 sites per year, visited annually, to illustrate trend detection sensitivity, nearly the same power can be achieved in a 10- to 20-year time frame with designs that use different patterns of visits to sites. Designs that incorporate a cyclical pattern of revisits to sites across years can be nearly as powerful as an annual design after three cycles (Urquhart et al. 1998; Urquhart and Kincaid 1999). For example, in a 4-year panel design, a different set of 50 sites would be monitored each year for 4 years. Then in year 5, the first year's sites would be revisited; in year 6, the second year's sites would be revisited, and so on. Adding some revisits within years and between adjacent years would allow estimation of the components of variation. An ongoing evaluation of variation would allow the design to be adjusted if the observed magnitude of the components of variation differed from that expected. Although panel designs are somewhat less sensitive to trend detection than annual visits, they have the advantage of visits to a larger number of different sites for essentially the same cost. The larger sample size greatly increases the utility of the network for assessing status and regional patterns and can allow for finer resolution in evaluating separate classes of streams. Survey designs that include visits on alternate years do not hamper trend detection sensitivity significantly; they only delay trend detection by a few years. Crucial to the success of various designs, however, is continuance of a consistent monitoring program over years. Trend detection capability increases dramatically with time. The actual details of the temporal design do not matter as much as a commitment to the long-term integrity of the survey.

Survey designs of the type implied here are also flexible with respect to the resource of interest. Our results cover a rather broad geographic range of streams across Oregon and Washington. Nevertheless, they suggest that subtle trends in habitat condition might be detectable. We do not mean to imply that a monitoring network of 30–50 sites across the Northwest can adequately address all of the many questions about changes in habitat condition in streams. However, research could focus on specific geographic subpopulations of streams, specific stream channel types within them (e.g., Montgomery 1999), or specific types of management actions. There might be interest in small headwater coastal streams in which wood and sediment recruitment would be expected to be high. Trends might be more visible for these attributes there. Similarly, particular channel types, such as low-gradient, "response" channels, might be expected to be more responsive to management actions than other channel types (Montgomery and MacDonald 2002). The surveys can be designed to monitor networks of sites within the channel type of interest. It is encouraging that fairly small trends should be detectable in reasonably short time frames.

Given the broad agreement on the importance of several key stream habitat features, the huge expenditures allocated to salmon restoration (U.S. General Accounting Office 2002), and the 10- to 20-year time frame over which subtle trends are likely to be detected, it seems wise to begin monitoring programs that focus, at a minimum, on a core set of habitat elements, recognizing that complete agreement on the exact set, and the field procedures for their measurement, is unlikely. An adaptive monitoring perspective could be adopted (Ringold et al. 1999) to allow for estimation of the important components of spatial and temporal variation and use of that information to refine the designs through an iterative process without losing the value of the data already collected. Compared with expenditures on various aspects of habitat restoration and protection, costs of monitoring are relatively minor. Furthermore, the cost effectiveness of monitoring programs can be greatly enhanced by initiating them soon, thereby capitalizing on the substantial effect that survey duration has on the ability to detect trends.

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References

Abbe, T.B., and Montgomery, D.R. 1996. Large woody debris jams, channel hydraulics, and habitat formation in large rivers. Regul. Rivers Res. Manag. **12**: 201–221.

Bartholow, J.M. 2000. Estimating cumulative effects of clearcutting on stream temperatures. Rivers, **7**: 284–297.

Bauer, S.B., and Ralph, S.C. 2001. Strengthening the use of aquatic habitat indicators in Clean Water Act programs. Fisheries (Bethesda), **26**: 14–25.

Beechie, T.J., and Bolton, S. 1999. An approach to restoring salmonid habitat-forming processes in Pacific Northwest watersheds. Fisheries (Bethesda), **24**: 6–15.

Beechie, T.J., and Sibley, T.H. 1997. Relationships between channel characteristics, woody debris, and fish habitat in northwestern Washington streams. Trans. Am. Fish. Soc. **126**: 217–229.

Bisson, P.A., Quinn, T.P., Reeves, G.H., and Gregory, S.V. 1992. Best management practices, cumulative effects and long-term trends in fish abundance in Pacific Northwest river systems. *In* Watershed management: balancing sustainability and environmental change. *Edited by* R.J. Naiman. Springer-Verlag, Seattle, Wash. pp. 189–232.

Bisson, P.A., Reeves, G.H., Bilby, R.E., and Naiman, R.J. 1997. Watershed management and Pacific salmon: desired future conditions. *In* Pacific Salmon and their ecosystems: status and future options. *Edited by* D.J. Stouder, P.A. Bisson, and R.J. Naiman. Chapman and Hall, New York. pp. 447–474.

Collins, B.D., Montgomery, D.R., and Haas, A.D. 2002. Historical changes in the distribution and functions of large wood in Puget Lowland rivers. Can. J. Fish. Aquat. Sci. **59**: 66–76.

Committee on Environment and Natural Resources. 2000. From the edge: science to support restoration of Pacific salmon. National Science and Technology Council, Washington, D.C.

Draper, N.R., and Smith, H. 1967. Applied regression analysis. 3rd ed. John Wiley & Sons, Inc., New York.

Federal Caucus. 2000. Conservation of Columbia Basin fish. Final Basinwide Salmon Recovery Strategy, 2000. Available from:

www.salmonrecovery.gov or Federal Caucus, c/o BPA-P, P.O. Box 3621, Portland, OR 97208, U.S.A.

Fox, D.R. 2001. Environmental power analysis — a new perspective. Environmetrics, **12**: 437–449.

Gerrodette, T. 1987. A power analysis for detecting trends. Ecology, **68**: 1364–1372.

Gibbs, J.P., Droege, S., and Eagle, P. 1998. Monitoring populations of plants and animals. BioScience, **48**: 935–940.

Gregory, S.V., Swanson, F.J., and McKee, W.A. 1991. An ecosystem perspective of riparian zones. BioScience, **40**: 540–551.

Harmon, M.E., Franklin, J.F., Swanson, F.J., Sollins, P., Gregory, S.V., Lattin, J.D., Anderson, N.H., Cline, S.P., Aumen, N.G., Sedell, J.R., Lienkaemper, G.W., Cromack, K., Jr., and Cummins, K.W. 1986. Ecology of coarse woody debris in temperate ecosystems. Adv. Ecol. Res. **15**: 133–302.

Huntington, C., Nehlsen, W.M., and Bowers, J. 1996. A survey of healthy native stocks of anadromous salmonids in the Pacific Northwest and California. Fisheries (Bethesda), **21**: 6–14.

Independent Scientific Group. 1999. Scientific issues in the restoration of salmonid fishes in the Columbia River. Fisheries (Bethesda), **24**: 10–19.

Kaufmann, P.R., and Robison, E.G. 1998. Physical habitat characterization. *In* Environmental Monitoring and Assessment Program — surface waters: field operations and methods for measuring the ecological condition of wadeable streams. *Edited by* J.M. Lazorchak, D.J. Klemm, and D.V. Peck. EPA/620/R-94/004F. U.S. Environmental Protection Agency, Office of Research and Development, Washington, D.C. pp. 77–118.

Kaufmann, P.R., Levine, P., Robison, E.G., Seeliger, C., and Peck, D.V. 1999. Quantifying physical habitat in wadeable streams. EPA/620/R-99/003. U.S. Environmental Protection Agency, Washington, D.C.

Kondolf, G.M. 2000. Assessing salmonid spawning gravel quality. Trans. Am. Fish. Soc. **129**: 262–281.

Lackey, R.T. 2000. Restoring wild salmon to the Pacific Northwest: chasing an illusion. *In* What we don't know about Pacific Northwest fish runs — an inquiry into decision-making. *Edited by* P. Koss and M. Katz. Portland State University, Portland, Oreg. pp. 91–143.

Larsen, D.P., Kincaid, T.M., Jacobs, S.E., and Urquhart, N.S. 2001. Designs for evaluating local and regional scale trends. BioScience, **51**: 1069–1078.

Lisle, T.E. 1987. Overview: channel morphology and sediment transport in steepland streams. *In* Proceedings of the Corvallis Symposium, Erosion and Sedimentation in the Pacific Rim. *Edited by* R.L. Beschta, T. Blinn, G.E. Grant, G.G. Ice, and F.J. Swanson. Publication 165. International Association of Hydrological Sciences, Wallingford, U.K. pp. 287–297.

MacDonald, L.H., Smart, A.L., and Wissmar, R.C. 1991. Monitoring guidelines to evaluate effects of forestry activities on streams in the Pacific Northwest and Alaska. EPA/910/9-91/001. U.S. Environmental Protection Agency, Region 10, Seattle, Wash.

Maser, C., and Sedell, J.R. 1994. From the forest to the sea: the ecology of wood in streams, rivers, estuaries, and oceans. St. Lucie Press, Delray Beach, Fla.

McIntosh, B.A., Sedell, J.R., Thurow, R.F., Clarke, S.E., and Chandler, G.L. 2000. Historical changes in pool habitats in the Columbia River basin. Ecol. Appl. **10**: 1478–1496.

Mitchell, S. 1999. A simple model for estimating mean monthly stream temperatures after riparian canopy removal. Environ. Manag. **24**: 77–83.

Montgomery, D.R. 1999. Process domains and the river continuum. J. Am. Water Resour. Assoc. **35**: 397–410.

Montgomery, D.R., and MacDonald, L.H. 2002. Diagnostic approach to stream channel assessment and monitoring. J. Am. Water Resour. Assoc. **38**: 1–16.

Naiman, R.J., Bilby, R.E., and Bisson, P.A. 2000. Riparian ecology and management in the Pacific coastal rain forest. BioScience, **50**: 996–1011.

National Research Council. 1996. Upstream: salmon and society in the Pacific Northwest. National Academy Press, Washington, D.C.

Nehlsen, W.M. 1997. Pacific salmon status and trends — a coastwide perspective. *In* Pacific salmon and their ecosystems: status and future options. *Edited by* D.J. Stouder, P.A. Bisson, and R.J. Naiman. Chapman and Hall, New York. pp. 41–52.

Nicholas, J.W. 1997. The Oregon plan for salmon and watersheds: Oregon Coastal Salmon Restoration Initiative. State of Oregon, Salem, Oreg.

Peterman, R.M. 1990. Statistical power analysis can improve fisheries research and management. Can. J. Fish. Aquat. Sci. **47**: 2–15.

Ralph, S.C., Poole, G.C., Conquest, L.L., and Naiman, R.J. 1994. Stream channel morphology and woody debris in logged and unlogged basins of western Washington. Can. J. Fish. Aquat. Sci. **51**: 37–51.

Reeves, G., Benda, L., Burnett, K., Bisson, P., and Sedell, J. 1995. A disturbance-based ecosystem approach to maintaining and restoring freshwater habitats on evolutionarily significant units of anadromous salmonids in the Pacific Northwest. *In* Evolution and the aquatic ecosystem: defining unique units in population conservation. *Edited by* J.L. Nielsen. Am. Fish. Soc. Symp. **17**: 334–349.

Ringold, P.L., Mulder, B., Alegria, J., Czaplewski, R.L., Tolle, T., and Burnett, K. 1999. Establishing a regional monitoring strategy: the Pacific Northwest Forest Plan. Environ. Manag. **23**: 179–192.

Robison, E.G., and Kaufmann, P.R. 1994. Evaluating two objective techniques to define pools in small streams. *In* Summer Symposium Proceedings, Effects of Human Induced Changes on Hydrologic Systems, 26–29 June 1994, Jackson Hole, Wyo. *Edited by* R.A. Marston and V.A. Hasfurther. American Water Resources Association. Urbana, Ill. pp. 659–668.

Rutherford, J.C., Blackett, S., Blackett, C., Sarto, L., and Davies-Colley, R.J. 1997. Predicting the effects of shade on water temperature in small streams. N.Z. J. Mar. Freshwater Res. **31**: 707–721.

Schmitten, R., Steele, W., Jr., and Jones, R.P. 1995. Proposed Recovery Plan for Snake River Salmon. U.S. Department of Commerce, National Oceanographic and Atmospheric Administration, National Marine Fisheries Service, Portland, Oreg. Available from NMFS, Northwest Region, 7600 Sand Point Way, NE, BIN C15700, Bldg. 1, Seattle, WA 98115, U.S.A.

Stevens, D.L., Jr., and Olsen, A.R. 1999. Spatially restricted surveys over time for aquatic resources. J. Agric. Biol. Environ. Stat. **4**: 415–428.

Tuchmann, E.T., Connaughton, K.P., Freedman, L.E., Moriwaki, B.B., and Brookes, M.H. 1996. The Northwest Forest Plan — a report to the President and Congress. U.S. Department of Agriculture Forest Service, Pacific Northwest Research Station, Portland, Oreg.

Urquhart, N.S., and Kincaid, T.M. 1999. Designs for detecting trend from repeated surveys of ecological resources. J. Agric. Biol. Environ. Stat. **4**: 404–414.

Urquhart, N.S., Paulsen, S.G., and Larsen, D.P. 1998. Monitoring for policy-relevant regional trends over time. Ecol. Appl. **8**: 246–257.

U.S. General Accounting Office. 2002. Columbia River Basin Salmon and Steelhead. Federal Agencies' Recovery Responsibilities, Ex-

penditures and Actions. GAO-02-612. U.S. General Accounting Office, Washington, D.C.
Wolman, M.G. 1954. A method of sampling coarse river-bed material. Trans. Am. Geophys. Union, **35**: 951–956.
Wood-Smith, R.D., and Buffington, J.M. 1996. Multivariate geomorphic analysis of forest streams: implications for assessment of land use impacts on channel condition. Earth Surf. Processes Landforms, **21**: 377–393.