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Geospatial techniques for developing a sampling frame of watersheds across a region

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Abstract

Current land-management decisions that affect the persistence of native salmonids are often influenced by studies of individual sites that are selected based on judgment and convenience. Although this approach is useful for some purposes, extrapolating results to areas that were not sampled is statistically inappropriate because the sampling design is usually biased. Therefore, in recent investigations of coastal cutthroat trout (*Oncorhynchus clarki clarki)* located above natural barriers to anadromous salmonids, we used a methodology for extending the statistical scope of inference. The purpose of this paper is to apply geospatial tools to identify a population of watersheds and develop a probability-based sampling design for coastal cutthroat trout in western Oregon, USA. The population of mid-size watersheds (500-5800 ha) west of the Cascade Range divide was derived from watershed delineations based on digital elevation models. Because a database with locations of isolated populations of coastal cutthroat trout did not exist, a sampling frame of isolated watersheds containing cutthroat trout had to be developed. After the sampling frame of watersheds was established, isolated watersheds with coastal cutthroat trout were stratified by ecoregion and erosion potential based on dominant bedrock lithology (i.e., sedimentary and igneous). A stratified random sample of 60 watersheds was selected with proportional allocation in each stratum. By comparing watershed drainage areas of streams in the general population to those in the sampling frame and the resulting sample (*n* = 60), we were able to evaluate the how representative the subset of watersheds was in relation to the population of watersheds. Geospatial tools provided a relatively inexpensive means to generate the information necessary to develop a statistically robust, probability-based sampling design.

Key words

aquatic ecosystems, coastal cutthroat trout, GIS, probability-based sampling, sampling frame, water resources geography.

1. Introduction

Concern about habitat degradation and species extirpation has focused interest on the physical and biological effects of land-use activities at broad regional scales (Christensen *et al*., 1996). In the U.S.A., some federal agencies have attempted to broaden the spatial scale for managing some biological resources (Beattie, 1996; Dombeck, 1996; Thomas, 1996). The Northwest Forest Plan is one example of an attempt to formulate a landscape-scale management plan (FEMAT, 1993; USDA and USDI, 1994). Similarly, recent proposed plans for managing state forest lands in western Oregon rely heavily on principles for managing across large spatial scales (ODF, 2001). Implementing landscape-scale management and monitoring will require substantial research and innovation. Many ecosystem components and their interrelationships are poorly understood in this region, and Northwest Forest Plan regulations are based on limited empirical data (FEMAT, 1993). Furthermore, there is growing recognition that the answers to many of these ecological questions are scale dependent (White and Pickett, 1985; Frissell *et al*., 1986; May, 1994).

Because space and time interact to influence communities and ecosystems, the scales of observation are critical to understanding and managing for habitat and species persistence (Frissell *et al*., 1986).

Habitat studies in both aquatic and terrestrial ecosystems have frequently been conducted at the local scale (Imhof *et al*., 1996), but form, function, and historical context of landscapes are essential for the management of ecosystems at a variety of spatial scales (Nichols *et al*., 1998; Swanson *et al*., 1988). Biological organization is influenced by processes operating at both local and landscape scales and, therefore, integration across scales is critical to our understanding and management of ecosystems (Dunning *et al*., 1992; Watson and Hillman, 1997; Wiley *et al*., 1997).

Despite a call for an increased emphasis on broader-scale, integrated research, most studies of fish habitat are still conducted at the local scale (e.g. transects and channel units; see Armantrout 1998). Protocols for examining these data in a broader context have not been adequately developed (Imhof *et al*., 1996; Poole *et al*., 1997; Smith *et al*., 1997). The paucity of information concerning fish/habitat relationships of coastal cutthroat trout (*Oncorhynchus clarki clarki*) at the landscape scale is the result of a combination of factors, including (1) the expense and logistical difficulties inherent to conducting research at broad spatial scales, (2) extensive heterogeneity that occurs at broader spatial scales, (3) difficulties associated with experimentally manipulating landscapes, and (4) previous failure to recognize the potential importance of landscape patterns on organisms (Pickett and Cadenasso, 1995; Root and Schneider, 1995; Wiley *et al*., 1997). Managing aquatic resources over greater portions of the landscape will require that these obstacles be surmounted.

The expense and logistical difficulties inherent at broader spatial scales are directly related to the spatial heterogeneity evident across the landscape. These complexities often dictate that only a subset of the landscape can be studied in detail, and this limitation requires a robust sampling design (Stevens and Olsen, 1999). In such cases a hierarchical approach to sampling can provide the context and scope of inference for the object of interest and a means to explore finer-scale processes influencing the observed variables (Imhof *et al*., 1996). For instance, the Northwest Forest Plan was developed to govern forest management across the Pacific Northwest region, but the watershed may be the most appropriate scale for management of aquatic resources (Reeves and Sedell, 1992; USDA and USDI, 1994).

A critical feature of a sampling design is that it incorporates the spatial context of the population by spreading the sample across the entire domain of the population (Peterson *et al*., 1999; Stevens and Olsen, 1999). One approach to sampling watersheds across a broader area is to think of each individual watershed as a natural unit (defined by a given range of drainage areas) in a two-dimensional domain. This approach allows the classification of individual watersheds that occupy a uniquely defined spatial location, and the target population is the set of all watersheds that occur in the defined region (e.g. western Oregon). Standard sampling procedures provide a means to subsequently select study watersheds from the population domain (sensu Hessburg *et al*., 1999; Peterson *et al*., 1999; Stevens and Olsen, 1999).

Development of a sampling frame of watersheds (list of sampling units) is not trivial, however, because the necessary digital data layers are seldom available. For instance, the Hydrologic Unit Code System (HUC; Seaber *et al*., 1987) would be appropriate for our use at finer levels of definition (catchment and subcatchment level; 7th- and 8th-field HUCs); however, in western Oregon, digital coverage is currently limited to the watershed scale or 5th-field HUC (40 000 - 250 000 hectares, ha; Seaber *et al*., 1987). An inter-agency team is working to delineate boundary locations for 6th- and 7th-field HUCs (subwatershed and catchment hydrologic-unit) in the state of Oregon, but they were not available for this study.

The purpose of this paper is to apply geospatial tools to identify a population of watersheds and develop a probability-based sampling design. We present an example in which a sampling frame was developed for watersheds in western Oregon that are above natural barriers to anadromous salmonids (Salomidae) and that support coastal cutthroat trout. The resulting sample is being used in the investigation of fine- and broad-scale relationships among upslope landscape characteristics, physical stream habitat, and the distribution and abundance of coastal cutthroat trout.

2. Methods

Initial efforts focused on developing a sampling frame of watersheds that displayed a diversity of geomorphic reach (Montgomery and Buffington, 1997) and segment (Frissell *et al*., 1986; Moore *et al*., 1997) characteristics and at the same time allowed multiple watersheds to be sampled during a single field season. Watersheds west of the Cascade Mountain Divide were delineated using the United States Geologic Survey (USGS) GIS Weasel software application (Viger, *et al*., 1998) with a 30-meter digital elevation model and minimum threshold size of 500 ha. The ultimate size of a watershed was determined by the location of the first downstream tributary junction with a minimum drainage area of 500 ha, and thus, watershed area varied depending on topography. This procedure yielded watersheds that were replicable and representative of changes in topography across western Oregon.

To identify watersheds containing isolated populations of coastal cutthroat trout, it was necessary to locate natural barriers (e.g. waterfalls and cascades) to the upstream movement of anadromous salmonids. No comprehensive database documenting barriers to upstream migration of fish existed for western Oregon when this project began. To establish barrier locations and fish species distributions, therefore, interviews were conducted with biologists and hydrologists, both current and retired, from the Oregon Department of Fish and Wildlife, U.S. Forest Service, U.S. Fish and Wildlife Service, and the U.S. Bureau of Land Management. Each resource specialist was presented with a series of maps representing the geographic area of his or her expertise. Maps showed subwatershed boundaries (4th-field hydrologic units) and the 1:100 000-scale stream network for Oregon. The approximate location of previously documented natural barriers to the migration of anadromous salmonids was identified and noted on the map. Information about fish occurrences in the portion of each watershed that was isolated above a barrier was ascertained from previous stream inventories and personal knowledge of individual resource specialists. Mapped barrier locations were geo-referenced using a geographic information system (GIS) and linked to the database containing fish species information (Gresswell *et al.*, 2000).

Watersheds without a barrier to fish movement were removed from the sampling frame; barriers defined the boundaries for remaining watersheds that supported isolated assemblages of coastal cutthroat trout. Because physiographic province and geology were expected to influence fish/habitat relationships across western Oregon, the above-barrier watersheds were grouped by ecoregion: Coast Range, Klamath Mountains, and Cascades (Pater *et al.*, 1998) and one of two erosion-potential classes. Our study focused on aquatic habitats in forested areas and, therefore, watersheds in portions of the Willamette Valley ecoregion that were dominated by agricultural lands (level IV ecoregions: Portland/Vancouver Basin, Willamette River and Tributaries Gallery Forest, and Prairie Terraces: Pater *et al.*, 1998) were eliminated. Remaining Willamette Valley watersheds (level IV ecoregion: Valley foothills) that were located to the west of the Willamette River were categorized with the Coast Range ecoregion. Watersheds east of the Willamette River were grouped with the Cascades ecoregion. High-elevation watersheds in the Cascades ecoregion (level IV ecoregions: Cascade Crest Montane Forest, Cascades Subalpine/Alpine, High Southern Cascades Montane Forest, and Eastern Cascades Slopes and Foothills: Pater *et al.*, 1998) were excluded from the study because non-native salmonids are present in many of those steams. The erosion potential of individual watersheds was based on the bedrock type (Walker and MacLeod 1991) at the centroid of the watershed. Watersheds were classified as having low erosion potential (igneous rock type) or high erosion potential (sedimentary rock type); watersheds with metamorphic bedrock were grouped based on parent material. A sample of 60 watersheds was selected in proportion to the number of isolated watersheds (with coastal cutthroat populations) occurring in each of the six strata. Sample size was limited by resource and time considerations.

3. Results

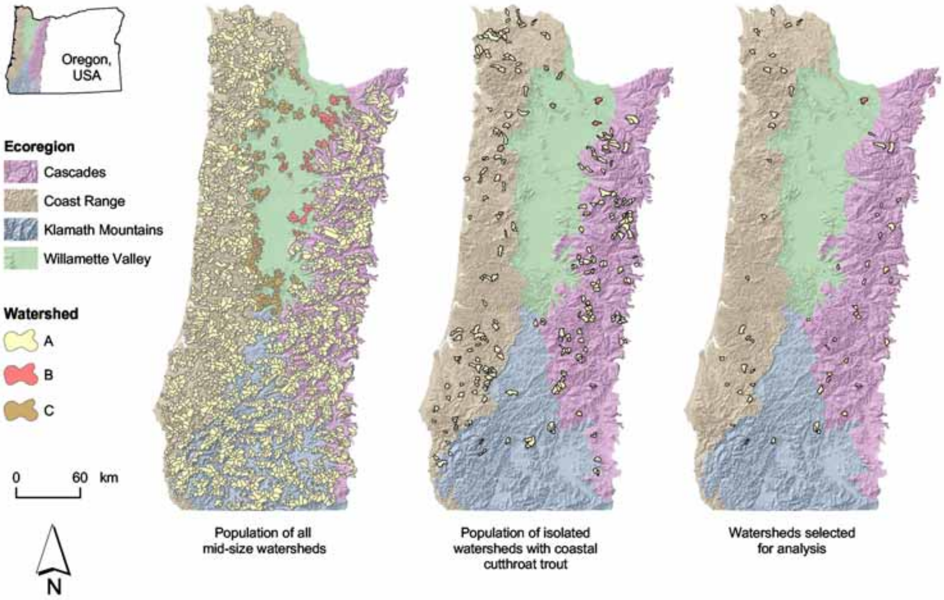
An initial total of 3171 watersheds was identified for western Oregon. Of these, 93 watershed boundaries are inaccurate. Visual examination of the watershed boundaries revealed that another 61 watersheds represent composite hydrologic units (i.e., an upstream watershed existed), and 339 watersheds have centroids that are outside the study area. Watersheds that are inaccurate or do not meet the selection criteria were not included in the final population.

After initial filtering, the database included 2678 watersheds (Map 1). The majority of the mid-size watersheds in western Oregon lie in the Cascades and Coast Range ecoregions (36% and 40%, respectively; Table 1), but the two ecoregions differ substantially in the proportion of watersheds with high erosion potential (20% and 80%, respectively). The Klamath Mountains ecoregion contains 24% of the watersheds, 51% of which are classified as highly erosive. Variation in mean watershed area is low within and among ecoregions, and mean area for individual ecoregion/erosion-potential classes ranges from 1041 ha (igneous watersheds of the Klamath Mountains) to 1357 ha (igneous watersheds of the Coast Range).

A sampling frame with 269 watersheds (500-5800 ha) that support coastal cutthroat trout upstream from natural barriers to anadromous salmonids was identified (Map 1). The proportion of watersheds with isolated assemblages is similar in the Cascades and Coast Range ecoregions (14% and 11%, respectively) but only 2% of the watersheds in the Klamath Mountains ecoregion had isolated populations of coastal cutthroat trout. With the exception of high erosion potential watersheds of the Klamath Mountains ecoregion, the mean drainage area of above-barrier watersheds supporting coastal cutthroat trout is larger than watersheds in the general domain of headwater drainages in western Oregon (Table 1).

Stratification by ecoregion and erosion potential yielded a sample (Map 1) that appeared to provide a realistic depiction of the gradient of geology, topography, vegetation, and climate in the region.

The proportion of watersheds selected for sampling varied from 21to 25% of the above-barrier watersheds that support coastal cutthroat trout in the Cascades, Coast Range, and low erosion potential portion of the Klamath Mountains ecoregions. Because there are only two watersheds with coastal cutthroat trout in the high erosion potential portions of the Klamath Mountains ecoregion, both (100%) were selected for sampling.



Map 1. Development of a sampling frame of watersheds across western Oregon. The population of all mid-size watersheds (500-5800 ha) was delineated in the Cascade, Coast Range, Klamath Mountains, and Willamette ecoregions of western Oregon (N = 2678); the population of watersheds that support coastal cutthroat trout upstream of natural barriers to anadromous salmonids (N = 269) was determined from existing data; 60 of these watersheds were selected randomly for analysis. The majority of all watersheds are located in the Cascades, Coast Range, and Klamath ecoregions (A); Willamette Valley watersheds east of the Willamette River were binned with the Cascades ecoregion prior to sample selection (B); Willamette Valley watersheds west of the Willamette River were binned with the Coast Range ecoregion prior to sample selection (C).

Drainage areas of selected watersheds in western Oregon do not differ statistically by ecoregion or erosion potential (Figure 1). It appears, however, that watersheds that support coastal cutthroat trout tend to be somewhat larger than the average size of watersheds in a particular ecoregion (Table 1 and Figure 1); the single exception occurs with watersheds from the Klamath ecoregion that have high erosion potential. As expected, the probability-based sample of watersheds exhibited watershed sizes that are similar to the sampling frame from which they were drawn (Figure1).

Table 1. Characteristics of the putative population of headwater drainages (>500 ha) in western Oregon, and the subset of those watersheds that support assemblages of coastal cutthroat trout above barriers to anadromous salmonids. Watersheds are categorized by ecoregion and erosion potential based on dominant bedrock geology in the drainage.

		Drainage Area (ha)							Proportion high erosion
Ecoregion	Erosion potential	Mean	Median	SE	Minimum	Maximum	N	Proportion of total (%)	potential (% of ecoregion)
Population of headwater drainages in western Oregon									
Cascades	High	1 229	1 020	53	540	4 881	189	7	20
	Low	1 237	1 083	56	504	7 156	768	29	
Coast	High	1 282	1 036	26	514	5 754	868	32	80
	Low	1 357	1 104	56	541	5 802	215	8	
Klamath	High	1 254	1 002	41	540	4 929	327	12	51
	Low	1 262	1 041	40	539	4 394	311	12	
Total							2678		
Population [of Watersheds (>500 ha) with isolated assemblages of coastal cutthroat trout									
Cascades	High	1 305	1 173	135	547	3 003	26	10	20
	Low	1 321	1 095	77	504	5 052	109	41	
Coast	High	1 419	1 172	88	544	5 754	94	35	78
	Low	1 414	1 300	113	612	2 321	26	10	
Klamath	High	1 091	1 091	427	664	1 519	2	1	14
	Low	1 912	1 359	309	825	3 640	12	4	
Total							269		
Random sample of watersheds from the population [of what?] of basins with isolated assemblages of coastal cutthroat trout									
Cascades	High	1 668	1 765	320	593	2 531	6	10	21
	Low	1 292	1 023	183	597	3 695	23	38	
Coast	High	1 308	1 081	159	587	2 918	20	33	77
	Low	1 487	1 527	272	612	2 258	6	10	
Klamath	High	1 091	1 091	427	664	4 519	2	3	40
	Low	1 470	1 165	484	825	2 419	3	5	
Total							60		

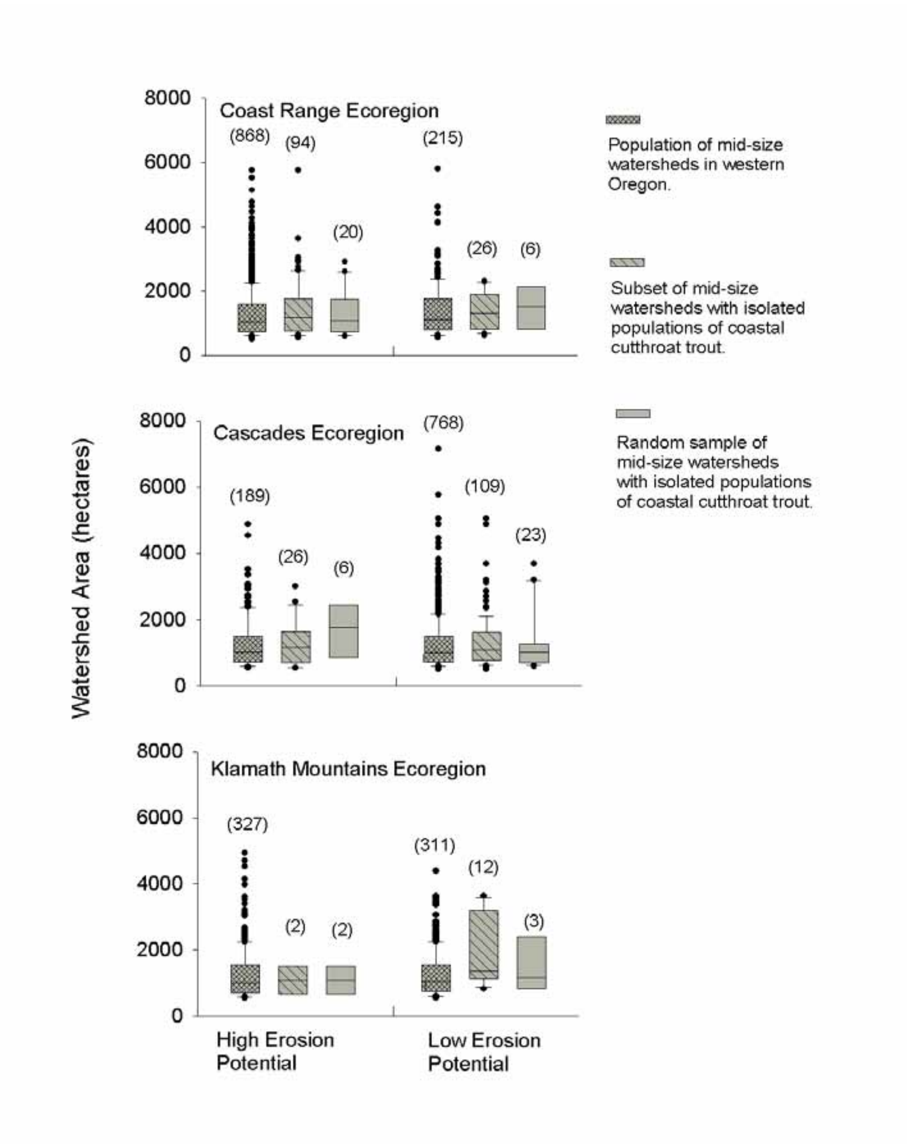


Figure 1. Box and whisker plots of watershed size (ha) for 2678 watersheds identified by the USGS GIS Weasel in western Oregon, the subset of 269 watersheds (500-5800 ha) that support coastal cutthroat trout upstream from natural barriers to anadromous salmonids, and 60 watersheds selected at random (in proportion to occurrence by ecoregion and erosion potential) from this subset for intensive field sampling. The box plot encompasses the interquartile range (25th and 75th percentiles), and the line drawn through the middle of the box is the median (the 50th percentile). The whiskers plot represents observations that were 1.5 times interquartile range; and solid dots indicate outliers > 1.5 times the interquartile range.

4. Discussion

In this study tools that are familiar to cartographers and GIS professionals were used to delineate watersheds at the regional scale. We were able to select a sample from the population with a known range of variation and defined scope of inference. Our goal was to evaluate the use of these readily available geospatial tools in the development of a probability-based sample of watersheds and share this practical application with other researchers, managers, and conservationists who may wish to initiate studies at broader spatial scales.

The GIS Weasel proved to be an easy-to-use, but explicit, geospatial tool that was effective for identifying the general population of watersheds in the region of interest. Although the GIS Weasel is easily obtainable (Viger, *et al*. 1998), we know of no other broad-scale ecological research project that has used this approach to evaluate how representative a statistical sample is in relation to the population from which it was selected. By identifying watersheds that support assemblages of coastal cutthroat trout, it was possible to develop a sampling frame for selecting an objective and representative sample of these watersheds. The resulting sample watersheds became the basis for the investigation of fine- and broad-scale relationships among upslope landscape characteristics, physical stream habitat, and the distribution and abundance of coastal cutthroat trout.

Because we sought to compare watersheds throughout western Oregon, selecting watersheds that are similar in size was important, but concomitantly, watersheds needed to be small enough to allow data collection within time-limits of the project. The selection of a small drainage area (500 ha) as a seed size for the GIS Weasel helped to constrain the delineated population to mid-size watersheds. Most of the resulting polygons (98%) encompassed an entire stream network draining to a single watershed outlet (i.e., true watershed; sensu. Maxwell *et al*., 1995). Composite watersheds (Maxwell *et al*., 1995), by definition, encompass more than one hydrologic unit of the same level (i.e., drainage area above the stream mouth [outlet] exceeds the limits of the hydrologic unit level of interest). Composite polygons met the size criterion, but because it was important to avoid an additional source of uncertainty that could confound planned among-watershed evaluations, these watersheds were excluded from further consideration.

The methodology used in this study is not without limitations, however, and the influence of topographic relief on the results of the GIS Weasel was problematic in several ways. For instance, because some stream nodes were not detected, estimates of watershed area sometimes exceeded expected sizes. Watersheds with areas of low topographic relief were often inappropriately combined with portions of adjacent watersheds. This problem would be expected to be even more troublesome if the initial size used to seed the algorithm were larger. On the other hand, a relatively minor investment of time was necessary to identify these errors and correct them manually. The GIS Weasel, or similar tools, will probably become even more useful as higher resolution digital elevation models become available.

The GIS Weasel proved to be a relatively inexpensive technique for generating precise information that is being used to investigate distributional patterns of coastal cutthroat trout at spatial scales ranging from local (channel units) to regional (western Oregon). In the process, we have assembled what is believed to be the most current and complete database describing the distribution of isolated coastal cutthroat trout populations in mid-size watersheds. This database has potential for application to a wide range of evolutionary and conservation issues, including genetic isolation, population persistence, and resilience to natural and anthropogenic disturbance. Furthermore, the steps used in our study can be repeated with little modification by other researchers who are interested in clearly defining the scope of inference in observational studies.

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