Marine Matters
Pacific Salmon Recovery Planning and the Salmonid Watershed Analysis Model (SWAM): A Broad-Scale Tool for Assisting in the Development of Habitat Recovery Plans

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Abstract
Pacific salmon in the lower 48 states, once numbering in the millions, are now counted by the thousands, the hundreds, and the tens (NRC, 1996). In the early 1990s, the National Marine Fisheries Service (also referred to as NOAA Fisheries), part of the National Oceanographic and Atmospheric Administration, was petitioned to list several salmon populations as endangered or threatened under the U.S. Endangered Species Act (ESA). As a result, status assessments were conducted for all anadromous Pacific salmon populations that migrate between the Pacific Ocean and their natal streams in Washington, Oregon, Idaho, and California. From these status assessments, NOAA Fisheries scientists identified 52 evolutionarily significant units (ESUs), the smallest population unit that can receive federal protection under the ESA. Of these 52 ESUs, 26 have been listed as endangered or threatened. Furthermore, it is estimated that scores of historic populations have become extinct. In this article, we provide a brief overview of salmonid life-history patterns and the importance of salmonids to the culture and ecology of the Pacific Northwest. We describe the recovery planning framework for salmonids, with an emphasis on the habitat components of recovery planning, and we present in detail one new tool, the Salmonid Watershed Analysis Model (SWAM), that has been applied as an early step in developing habitat recovery plans for many of the basins in which listed salmonids live.

Resumen
El salmón del Pacífico que anteriormente existía por millones en 48 estados de los Estados Unidos (ésto es, sin incluir Alaska y Hawaii), se cuenta ahora sólo por millares, centenares y decenas. A principios de los años noventa, el "National Marine Fisheries Service" (Servicio Nacional de Pesca Marina, NMFS), el cual es parte de la "National Oceanographic and Atmospheric Administration" (Administración Nacional Oceanográfica y Atmosférica, NOAA), recibió la petición de listar bajo el "Endangered Species Act" (Acta de Especies en Peligro de Extinción, ESA) de los Estados Unidos, como poblaciones en peligro de extinción o amenazadas a varias poblaciones de salmón . Como resultado de la petición, se llevó a cabo una valuación del estatus para todas las poblaciones de especies anadrómicas que migran entre el océano Pacífico y los ríos y arroyos natales en Washington, Oregón, Idaho y California. Con estas evaluaciones del estatus de poblaciones, los científicos de NMFS (también llamado "NOAA Fisheries") identificaron 52 "evolutionarily significant units" (unidades significativas en términos de su evolución, UES). UES es la más pequeña unidad poblacional que puede recibir protección federal bajo el ESA. De estas 52 UES, 26 han sido listadas como unidades en peligro de extinción o amenazadas. Además, se estima que veintenas de poblaciones históricas se han extinguido. En este artículo, damos un breve resumen de los patrones del ciclo de vida de los salmónidos y la importancia de éstos para la cultura y ecología del Noroeste Pacífico. Describimos el modelo de plan de recuperación, y presentamos en detalle una nueva herramienta llamada "Salmonid Watershed Analysis Model" (Modelo de Análisis de Cuencas de Salmónidos, SWAM), la cual ha sido aplicada como una etapa previa al desarrollo de planes de recuperación de habitat para muchas de las cuencas en las cuales viven los salmónidos listados.

Résumé

Les saumons de Pacifique, dans les Etats-Unis contigus, à une temps comptent dans les millions, comptent actuellement par milliers, les centaines, et les dizaines. Au début des années 90's, le "National Marine Fisheries Service" (le NOAA Fisheries), une partie de "National Oceanographic and Atmospheric Administration", a pétitionné de faire la liste de plusieurs populations de saumons comme des espèces en voie de disparition ou menaces sur le "US Endangered Species Act" (ESA). En conséquence, les évaluations de statu pour toutes les populations des saumons Pacifiques et « anadromous » qui migrent entre le Pacifique et leurs ruisseaux dans le Washington, l'Oregon, l'Idaho, et en Californie. De ces évaluations de statu, NOAA Fisheries a identifié 52 des unités importantes dans le monde d'évolution (ESU), l'unité de population la plus petite qui peut recevoir la protection fédérale sous le ESA. 26 de ces 52 ESU ont énuméré comme des espèces en voie de disparition ou des espèces menacées. De plus, il évaluait que des tas des populations historiques sont devenues disparu. Dans cet article, nous présentons une vue d'ensemble des modes de vie historique et l'importance des saumons a la culture et l'écologie du Nord-Ouest Pacifique. Nous décrivons la structure de la planification de rétablissement pour les saumons, avec emphase sur les composants de l'habitat de la planification de rétablissement, et nous présentons en détail un nouvel outil, le "Salmonid Watershed Analysis Model" (SWAM), qui a été appliqué comme une mesure tôt dans le développement des planifications de rétablissement de l'habitat pour plusieurs des bassins en lesquels les salmonids énumérés habitent.

Salmon and their Importance to the Pacific Northwest

There are seven species of salmonids living in the Pacific Northwest – coho (*Oncorhynchus kisutch*), chinook (*O. tshawytscha*), chum (*O. keta*), sockeye (*O. nerka*) and pink (*O. gorbuscha*), as well as anadromous steelhead (*O. mykiss*) and cutthroat (*O. clarki*) trout. Each species is made up of one or more evolutionarily significant units (ESUs), which are composed of one or more populations (Figure 1). In most cases, populations correspond roughly to traditional distinctions between stocks used by fisheries management agencies. By definition, independent populations must be reproductively isolated; therefore, salmonid population boundaries are normally delineated using spawning location. The geographic range of a population's spawning area depends on local geography, stream morphology, and, perhaps most importantly, population life history characteristics.

Figure 1. Map of total area occupied by ESA listed anadromous salmonids. Map compiled from various maps of ESA listed anadromous salmonid species (NMFS 2002). These source maps depict major river basins within the current known range of the species or ESU. The various species do not necessarily inhabit all drainages or river reaches depicted. Data for analysis and display were compiled from the best available sources and are for general reference only.

Salmonids have unique life-history patterns that make them at once vulnerable to ecosystem alterations yet highly adaptable to a wide variety of habitat conditions. Salmon build nests in gravel of freshwater streams, lakes, and rivers. The young emerge as fry and, in species such as chum or pink salmon, migrate almost immediately to the near-shore or ocean environment. Other species, such as sockeye salmon, coho salmon, and steelhead, may rear for a year or more in freshwater, often migrating between freshwater habitats before the final migration to the sea. Chinook salmon exhibit a variety of emigration strategies, displaying a range of migrant ages from fry to two-year olds, depending on the population and on local conditions. Most salmonids feed and grow in the ocean, though a few species (e.g., sockeye salmon and steelhead) have life-history variants that remain in freshwater and never migrate (e.g., kokanee and rainbow trout respectively). All species return to their natal streams to deposit eggs; most species are semelparous, spawning once before dying, though some steelhead and most cutthroat trout are iteroparous, maintaining the ability to migrate back to sea after spawning and to return to spawn again. The variability in life-history patterns within and among species and populations enables salmon to utilize multiple habitat types within a watershed; thus, the requirements of individual populations can be important to effective management. For example, those species and populations with an extended freshwater residence seem to be most susceptible to habitat degradation (NRC, 1996). The wide variety of life-history trajectories makes management of multiple listed stocks within a single watershed both critical and challenging.

Salmon are at the cultural, economic and recreational center of many Pacific Northwest communities. For centuries, local tribal communities have relied on salmon for subsistence. Today, many of those tribes continue to rely on salmon as a primary source of revenue. As an economic resource, salmon are an important regional industry. There were estimated to be over 8,000 full-time work years involved in the West Coast salmon industry in the early 1990s (NRC, 1996). However, the economic value of salmon fishing has been declining with salmon population declines. The value of West Coast commercial landings at first sale was estimated at $98 million in 1979 and dropped as low as $6.6 million by 1994 (NRC 1996). Recreational fishing, along with its related industries, provides further economic resources to the region; these industries have also been affected by salmon population declines (NRC 1996). In addition to their cultural and economic benefits, salmon help maintain a healthy ecosystem. Adult salmon returning from the ocean to spawn bring with them nutrients that contribute to the growth of aquatic and terrestrial plants and animals and to the next generation of salmon (Bilby et al. 1996, Bilby et al. 1998, Helfield and Naiman 2001).

The Pacific Northwest has been dramatically altered by humans; its watersheds have been extensively diked, channelized, dammed, logged, mined, farmed and urbanized (Beechie et al. 1994, Sedell and Luchessa 1982). There are multiple hydro-electric dams on major rivers. The Pacific Northwest depends on hydropower for approximately 90% of its electrical energy (NRC 1996). These alterations, in combination with a long history of commercial fishing exploitation, have been identified as chief causes for the decline of salmon populations in the region (NRC 1996).

Recovery Planning

One of the main purposes of the Endangered Species Act (ESA) of 1973 is "to provide a means whereby the ecosystems upon which endangered species and threatened species depend may be conserved." For ESA-listed salmon in the Western United States, this requirement is no small task; salmon habitat is ubiquitous and the actions required to protect or restore the ecosystems on which salmon depend are in conflict with nearly every land use in the region.

Over the past decade, many scientists have pointed out that the approach for managing salmon and other species listed as threatened or endangered has focused on individual species and habitat characteristics, rather than on whole ecosystems (e.g., Doppelt et al. 1993, Frissell et al. 1997). It has also been recognized by scientists and managers alike that restoration plans that carefully consider the watershed or ecosystem context are most likely to be successful at restoring individual or multiple species and preventing the demise of others (Nehlsen et al. 1991, Doppelt et al. 1993, FEMAT 1993, Lichatowich et al. 1995, Reeves et al. 1995, Beechie et al. 1996, Moore 1997). These conclusions suggest that habitat recovery planning will require assessments of disruptions to ecosystem functions and biological integrity, which have reduced the productive capacity of Pacific Northwest river systems and are partly responsible for the declines in salmon abundance. With this approach, restoring specific salmon populations (or any other single organism) is subordinate to the goal of restoring the ecosystem that supports multiple salmon species. In addition, information on habitat changes or conditions that limit specific salmon populations can be useful for identifying actions that may have the greatest effect on salmon recovery (e.g., Reeves et al. 1991), or for helping to set population and ESU recovery goals. As long as all restoration actions are consistent with the overriding goal of restoring ecosystem processes and functions, habitats will eventually be restored for multiple species, but the sequence of actions may favor one species over the others (Beechie et al. In Prep).

NOAA Fisheries is tasked with recovery planning for Pacific salmon, including habitat recovery planning, for species listed under the ESA that spend all or part of their life in the marine environment; therefore anadromous salmonids are under the jurisdiction of NOAA Fisheries. Non-anadromous species in the same watershed, and often in the same stream, are under the jurisdiction of the United States Fish and Wildlife Service (USFWS). Recovery planning over such a wide and diverse geographic area and for multiple species, each with differing habitat requirements and multiple life-history stages, is a challenge. NOAA Fisheries has divided the region into nine recovery domains and appointed a Technical Recovery Team (TRT) for each domain. These TRTs are tasked with developing the technical aspects of a recovery plan for each ESU within the recovery domain.

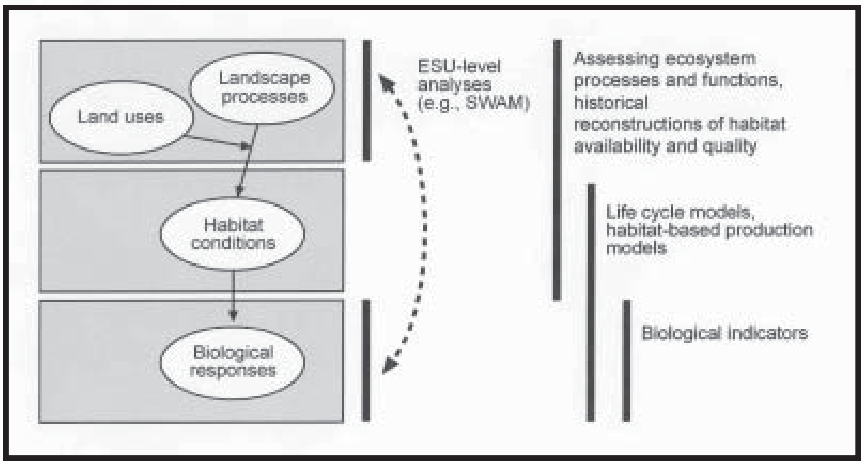


Figure 2. Schematic diagram of linkages among landscape processes, land use, in-stream habitat, and biological responses. For ESU-wide analyses of land use effects on salmon populations, landscape and land use factors can be correlated with indicators of population performance (e.g., SWAM) (Modified from Beechie et al. In Prep.).

The ESA provides limited guidance concerning the content of recovery plans for individual species. Three documents produced by NOAA Fisheries provide additional guidance on recovery planning needs and related scientific concepts. Scientific guidance on setting population recovery goals (McElhany et al. 2000) is based on the concept of viable salmonid populations (VSPs). McElhany et al. (2000) identify four types of goals that must be met in order for a population to be considered viable: abundance; productivity; spatial structure; and diversity. The TRT Guidance Document (NMFS 2000) written by NOAA Fisheries provides detailed information on recovery planning needs. With respect to habitat, this document indicates that an important step in recovery planning is to characterize habitat/fish productivity relationships. This includes assessing the spatial distribution of fish abundance for each population in the ESU, associating fish abundance with habitat characteristics, and identifying human factors that have the greatest impact on key freshwater and marine habitat. However, it does not specify appropriate spatial scales or resolution of data analyses. Lastly, the Watershed Program within the Northwest Fisheries Science Center, in coordination with the TRTs, has nearly completed a NOAA Fisheries Technical Memo, Ecosystem Recovery Planning for Listed Salmon: An Integrated Assessment Approach for Salmon Habitat, which is currently available in draft form on the web at http:// www.nwfsc.noaa.gov/ec/wpg/reports.htm. This document provides a template, scientific considerations, and examples of analyses for developing the habitat component of recovery plans. The document aims to provide tools that can aid in initiating restoration activities that provide for ecosystem-based recovery rather than single-species, short-term, or engineered solutions (Beechie et al. In Prep). A general framework for understanding relationships between watershed processes, land-use, in-stream habitat, and fish populations is provided in the document and forms the underlying working hypothesis of our modeling framework (Figure 2).

The Salmonid Watershed Analysis Model (SWAM)

Relating watershed-scale habitat conditions to fish population response is challenging. Methods based on habitat capacity have been developed in the Pacific Northwest (Reeves et al. 1989, Beechie et al. 1994), but have not been used for regional analyses because they require detailed field data that are not available across all watersheds. Various methods of stream habitat classification also have been used to predict salmon response to habitat condition. For example, a priori classification of channel types can explain substantial variance in salmonid spawner densities (Montgomery et al. 1999), but other important habitat variables also influence salmonid population dynamics such as stream temperature and land-use. Salmon population size usually varies dramatically from year to year due to changes in marine survival and correlation between cohorts. This variability further complicates efforts to link habitat conditions to fish response.

The Salmonid Watershed Analysis Model (SWAM) was developed in response to these challenges. It is a series of spatial and statistical analyses that relate salmonid population counts (e.g., redd counts, adult counts, juvenile counts) at index reaches in a particular basin to coarse-scale habitat characteristics derived from existing geospatial data layers. SWAM identifies large-scale habitat features (anthropogenic and natural) correlated with fish abundance in a given subbasin. It provides a predictive model of where the highest densities of fish in a particular basin are likely to occur, a series of ecological hypotheses about factors driving salmon abundances in a particular basin, and a list of important factors to control for when setting up monitoring projects or management experiments.

SWAM characterizes the relationship between habitat and salmon populations in a given subbasin. The response variable is a time series of fish or redd (salmon nest) counts collected at numerous reaches in that subbasin. Predictive variables consist of habitat data characterized from geospatial data layers of land use type (e.g., grazing, water diversions, logging, mining, urbanization), landscape characteristics (e.g., geology, topography, vegetation), and climatic conditions (e.g., air temperature, precipitation). Consistent relationships between habitat and salmonid abundance over time are then used to predict relative salmonid densities in areas of the subbasin that lack abundance data.

SWAM has been applied in the Salmon River basin in Idaho (Feist et al. In Review), the Snohomish (Pess et al. 2002), Yakima, and Wenatchee River basins in Washington, and the John Day and Willamette River basins in Oregon. The spatial and statistical analyses are similar between basins and are comprised of five steps. (1) Conceptual relationships between coarse-scale habitat features and population abundance during freshwater life-history stages are identified from the literature and from local habitat biologists. These conceptual relationships define which available habitat characteristics will be used as potential predictor variables in the spatial analysis. (2) Spatial heterogeneity in the salmonid abundance data over time is examined to determine if particular areas in the basin consistently exhibit higher fish densities than other areas (Figure 3). (3) Habitat characterization data layers are overlaid with the geo-referenced fish abundance data (e.g., redd counts) (Figure 4). By defining multiple areas of influence, habitat can be characterized at multiple spatial scales, for example, reach and landscape scales. (4) A statistical model is developed to describe annually consistent relationships between habitat characteristics and fish abundance. (5) Predictions based on the model are made for areas within the basin for which no fish data exists.

The SWAM approach differs from previous extrapolation attempts in three important ways: (1) It uses

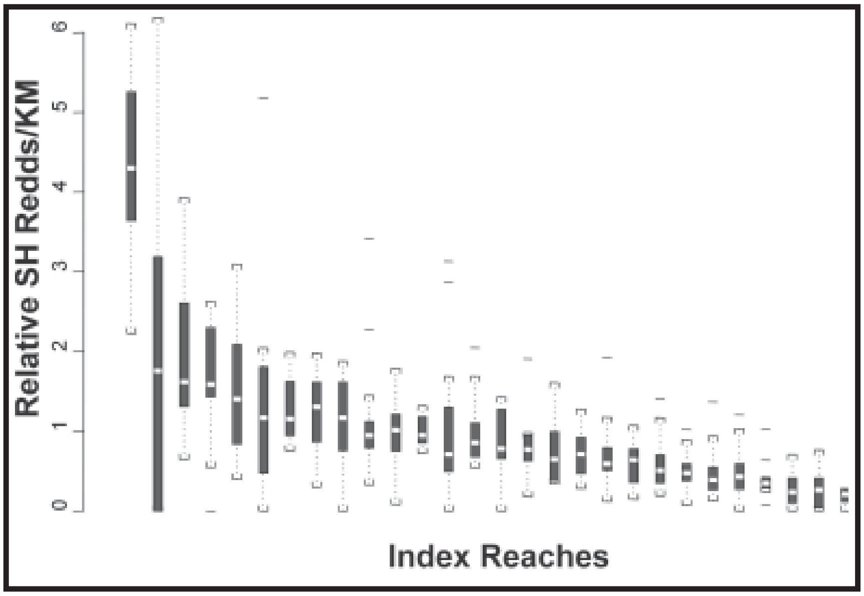


Figure 3. Distribution of steelhead redds by index reach from 1979-1999 in the Santiam, Calapooia, and Molalla watersheds within the Willamette River basin. Relative number of steelhead redds was calculated as the fraction of redd density observed in a particular year within a particular reach divided by the redd density observed over all reaches surveyed in that year.

salmon abundance rather than presence/absence data and is based on existing long-term surveys, (2) It measures habitat from existing GIS data layers using a flexible area of influence, (3) It uses a statistical technique that extracts the most information from the data and explicitly describes model and prediction uncertainty.

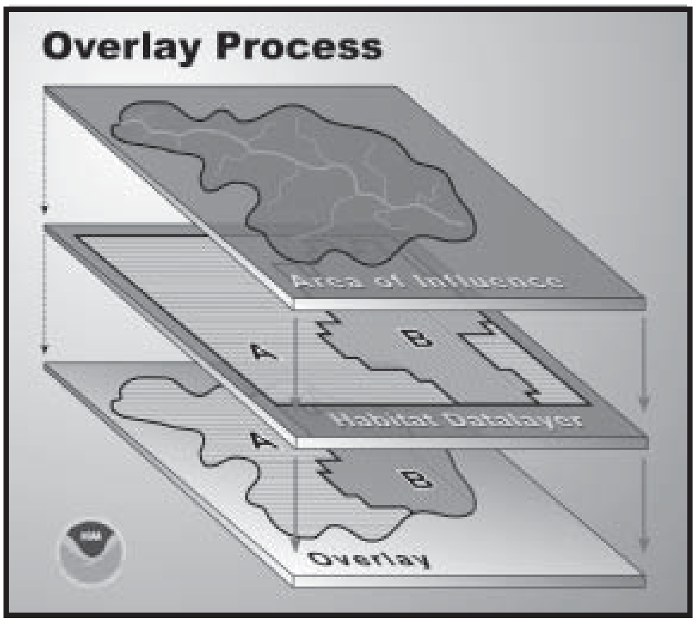


Figure 4. Schematic representation of GIS datalayer overlay process used to determine the fraction or percent area covered by various habitat categories in a given watershed associated with a given index reach.

General SWAM Results

We found that salmonid distribution across basins is temporally consistent. In all basins, certain reaches consistently supported a larger fraction of the population than other reaches (Figure 3). This pattern could be detected through years of both high and low population abundance. Identifying the pattern is dependent on having a long time-series of fish or redd counts at a consistent set of index reaches.

We also found that conclusions about which habitat attributes had the greatest influence on salmon abundance were a function of the area of influence. For example, if we had done our analyses using only a reach area of influence (characterizing habitat within 500 m of the stream channel) in the Salmon River, we would have concluded that ambient air temperature was the primary driver of spawner density. By also running our analyses for the watershed area of influence (characterizing habitat over the entire watershed that drains to the index reach), we learned that descriptors of vegetation as well as geology and terrain influence salmon abundance (Feist et al. In Review). Analysis scale also influences model fit. In analyses of chinook salmon in the Wenatchee River basin, models using habitat data characterized over the reach area of influence had a poor fit as compared to models using habitat data characterized over the entire watershed.

In all the basins, our results are consistent with our underlying working hypothesis that watershed-scale features describing climate, geology, and land-use affect many of the in-stream conditions determining fish abundance (Table 1). Geomorphic features control such site-specific factors as stream width, alkalinity and stream slope (Isaak and Hubert 2001), each of which affects the suitability of a particular reach for spawning or rearing. Climate can regulate flow and water temperature, and land-use has the potential to modify nearly every aspect of in-stream habitat conditions.

Potential Uses of SWAM for Recovery Planning

Recovery planning for listed salmonids is being carried out in two phases. Phase I recovery-planning actions consist of setting recovery benchmarks such as biological de-listing goals. Phase II actions are aimed at developing a detailed list of actions (e.g., habitat protection or restoration, and harvest or hatchery regulations) required for recovery of each ESU. Models are being employed in both steps because of the broad geographic areas involved, the complexity of salmonid life-history patterns, the lack of adequate field-based data, and the need for predictions about habitat change and population response. SWAM assessments have uses in both phases of recovery planning. In Phase I, they may provide habitat-based estimates of average population size for comparison to estimates from population viability analyses. In Phase II, they can indicate which habitat conditions are correlated with declines in salmon populations, and therefore, which categories of restoration actions might result in increased salmon populations. They can also estimate the potential of currently inaccessible or unstudied habitat for supporting salmonids.

SWAM results can help plan small-scale restoration in the context of whole watersheds. For example, removing anthropogenic barriers to fish passage has been identified as a restoration action with a high likelihood of success and a very low likelihood of negative impacts (except for impacts on the resident fish populations when they are suddenly re-exposed to competition with anadromous fishes) (Roni et al. 2002). Therefore, barrier removals are one of the best actions to initiate during the first stages of recovery management. Observations of fish use of habitats above barriers being considered for removal are not possible, presenting a difficult problem. Using remotely sensed data and SWAM-based predictions of potential occupancy in currently inaccessible areas, a series of prioritization schemes for barrier removal projects can be developed. While model-based prioritization schemes cannot substitute for detailed field analysis, they can greatly reduce the time required for such field surveys by identifying a set of projects most likely to be successful.

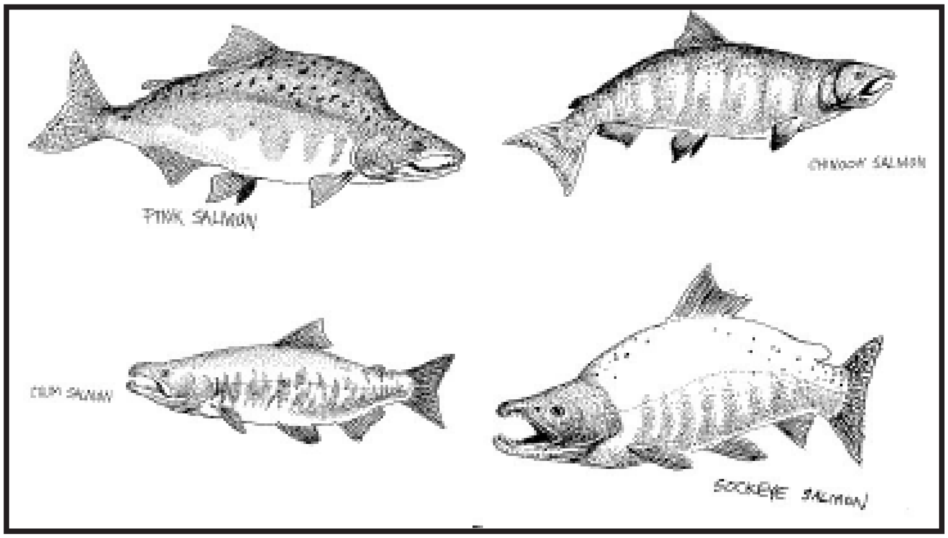
In the Snohomish River basin, our analysis provides a method to identify which habitat attributes correlate with the greatest adult coho salmon abundance (Pess et al. 2002). The SWAM results can be used as a coarse-screening tool for several purposes. For example, results could be used to identify sites, currently impaired by land use, which could potentially have greater abundance levels. Restoration activities might then be prioritized to address first those impaired locations that are predicted to have the appropriate habitat attributes for supporting high salmon abundances. Results might also be used to identify areas with a predicted high abundance of salmonids and a high risk of habitat degradation in the future. These sites might provide a first estimation of areas for conservation and protection. In both cases, on-the-ground assessments should be used to validate model predictions.

Predictor Variable	Chinook Salmon				Steelhead	
	Yakima	Wenatchee	Salmon	John Day	John Day	Willamette
Channel Gradient	X	X				
Hill Slope†		X	X			X
Riparian Vegetation	X		X			
Shrublands						X
Conifer Forest < 40 yr						
Alpine Vegetation	X				X	
Open Water		X				
Ponderosa Pine		X				
Successional Forest		X				
Agriculture	X					X
Urbanization				X		
Dam Density	X	X				
Mine Density		X				
Cattle Grazing				X	X	
Sheep Grazing					X	
Minimum Air Temp.			X			
Maximum Air Temp.			X			
Precipitation					X	
Alluvium		X				X
Landslide-derived Geology						X
Mafic Volcanics						X
Sedimentary Geology			X	X		
†< 6% for steelhead, < 1.5% for chinook salmon						

Table 1. Landscape variables used to predict redd densities in 5 subbasins of the Columbia River. All variables except channel gradient, air temperature, precipitation, dam density and mine density describe the proportion of the index reach watershed composed of that feature.

SWAM analyses describe relationships between broad-scale habitat characteristics and salmon population patterns. The models can help identify areas most likely to be successful for salmon spawning or rearing. Like all models, SWAM is limited by available data. Most abundance surveys were not conducted in low quality habitats where there are low numbers of fish. As a result, SWAM models currently characterize areas which comprise some of the better habitats for fish and predict the best of these already good habitats. Sampling protocols specifically designed to understand relationships between habitat condition or habitat change and fish populations will require random sampling procedures and time series of habitat change. SWAM models can easily accommodate such new data when it exists.

The use of large-scale analyses in management of endangered species is gaining momentum. Large-scale models predicting the presence and absence of butterflies (Cowley et al. 2000) have provided conservation biologists with management tools that can substitute for expensive, detailed field analyses where they are lacking. Other GIS-based approaches to identifying salmon spawning habitat have been or are being developed (e.g., Lunetta et al. 1997). Examining patterns of abundance or survival at larger scales represents a new opportunity for understanding patterns of fish distribution and for making predictions about where in a watershed large numbers of fish might thrive (Poff and Huryn 1998). The SWAM approach has both scientific interest for exploring and understanding how fish are distributed as well as immediate management applications.



Pacific salmons. Art by Bob Savannah. Courtesy of U. S. Fish and Wildlife Service

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