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Northwest Fisheries Science Center

SUMMARIES FOR THE SALMON HABITAT IN RECOVERY PLANNING (SHRP) DOCUMENT, THE CHINOOK SALMON LIFE CYCLE MODEL, AND THE SALMONID WATERSHED ANALYSIS MODEL (SWAM)

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This document provides a summary of some of the recent research and thinking within the Northwest Fisheries Science Center's Watershed Program relevant to habitat recovery planning. We put this document together to provide an overview of three projects: technical guidance on incorporating habitat in recovery planning, salmon life-cycle modeling, and landscape scale assessments of the relationship between salmon abundance and landscape features. The intended audience includes both technical staff and natural resource managers.

Brief Summaries:

1) Salmon Habitat in Recovery Planning (SHRP) – Is a NOAA Technical Memorandum providing guidance on habitat components of recovery planning. The conceptual approach is based on an understanding that salmon are adapted to local environments and therefore that habitat recovery that focuses on preserving or restoring ecosystem processes should provide quality salmon habitat over the long-term. Chapters include discussions of habitat analyses for Phase I and Phase II recovery goals, prioritizing restoration actions, and uncertainty in recovery planning, issues of scale in recovery planning and example analyses are provided in the appendices. http://www.nwfsc.noaa.gov/ec/wpg/reports.htm.

2) Chinook Salmon Life Cycle Model – A watershed-scale life-cycle (Leslie matrix model) approach for estimating sources of mortality for chinook salmon in the Skagit River basin and potential consequences of improving aquatic habitats used by salmon. The model specifies residency and survival in spawning nests (redds), streams, tidal deltas, nearshore habitats, and the ocean. The relative importance of different habitats under three density-dependent scenarios was compared in a draft manuscript that has been submitted for publication.

3) Salmonid Watershed Analysis Model (SWAM) - SWAM 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 datalayers. SWAM identifies large-scale habitat features (anthropogenic and natural) correlated with fish abundance in a given subbasin. It can provide a map (Figure 6) 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, predictions of potential relative redd densities in currently inaccessible areas, and a list of important factors to control when setting up monitoring projects or management experiments. SWAM analyses have been published for the Snohomish River basin, are in review for the Salmon and Willamette River basins. Initial analyses have also been completed in the Wenatchee, John Day, and Yakima River basins.

1) SALMON HABITAT IN RECOVERY PLANNING FAQs

The following set of Frequently Asked Questions about Salmon Habitat in Recovery Planning (SHRP) (Beechie et al 2002) provides a summary of the purpose and the content of the document. The full report is available in draft on the web at http://www.nwfsc.noaa.gov/ec/wpg/reports.htm.

What is the purpose of SHRP?

The SHRP document is designed to provide guidance on habitat components of recovery planning. Specifically, SHRP describes a conceptual framework for understanding linkages among landscape and watershed features, land uses, habitat, and salmon populations, and presents an integrated suite of assessment tools for identifying and prioritizing ecosystem recovery needs. The document provides key questions and describes data collection and analysis techniques useful for answering these questions. SHRP was written to describe types of habitat analyses that can inform biological delisting criteria (e.g., quality and quantity of habitat and level of salmon viability necessary for recovery), and types of analyses that can help identify and prioritize habitat conservation (restoration and protection) actions necessary for recovery (i.e., address the threats that likely caused the species to be listed).

Who are the intended audience for the SHRP document?

SHRP is primarily intended for parties involved in development of recovery plans and associated restoration activities for threatened and endangered Pacific salmon (including steelhead). These include Technical Recovery Teams (TRT), local watershed planning groups (e.g., watershed councils), state and county regulators, private citizens, and National Marine Fisheries Service (NOAA Fisheries) and other Federal Agency personnel.

How is the SHRP document different than the guidance already provided, such as the Washington State Guidance on Watershed Assessment for Salmon?

The guidance provided in SHRP is not intended to be specific to any state or region, but to be used for restoration planning for all listed Pacific salmonids. The SHRP document emphasizes process-based methods rather than a static habitat restoration approach.

What is the relationship of SHRP to existing habitat assessment tools?

There are several existing and frequently used habitat assessment tools (e.g., Ecosystem Diagnosis and Treatment, limiting factors analysis, life-cycle models, and correlation models). To complete the full scope of analyses described in SHRP, several different assessment tools will likely need to be employed. A list of questions that an assessment could answer is provided in the SHRP document.

Does SHRP provide a standard methodology for all planning entities to follow?

No. SHRP is not a "cookbook", one-size-fits-all, habitat restoration manual. An entity using the SHRP guidance to develop restoration methods associated with a recovery plan can apply those concepts and tools appropriate to the specific planning area, taking into account local needs and ongoing assessments and restoration activities.

Do ongoing assessments and habitat restoration activities conflict with those described in SHRP?

No. The authors of the SHRP document did not intend that their approach should replace ongoing activities. Rather, the habitat assessments and restoration tools described in SHRP should provide a context in which planning entities can examine and evaluate their ongoing assessments and habitat restoration activities. Planning entities will be able to use the results of existing and ongoing assessments and determine which additional assessments or modifications to existing assessment methods might be necessary to provide a complete analysis of the planning area. The results of all of these analyses can be used to conduct a similar gap analysis of existing and ongoing habitat restoration activities to identify and prioritize future activities.

Does the Watershed Program recommend the SHRP approach for habitat analysis and restoration planning for all Pacific salmon recovery planning?

The Watershed Program believes that the SHRP approach will provide useful information to develop strong habitat components of recovery plans. The Watershed Program also recognizes, however, that other guidance on habitat recovery exists and does not preclude its use in developing sound recovery plans.

What is the SHRP conceptual model?

The conceptual framework behind the habitat assessments described in SHRP is simple. Specifically, land uses may influence ecosystem processes, and ecosystem processes shape local habitat conditions, which in turn affect viability of salmon populations. By focusing habitat restoration activities on ecosystem processes that form habitat (instead of on restoring individual sections of habitat that might not persist through time), long-term restoration of the habitat conditions can occur, allowing salmon to fully utilize previously degraded habitats. This concept is based on the premise that salmon are adapted to local conditions, including associated inherent variability. This approach is broad enough not only to satisfy requirements of Endangered Species Act (ESA) and other environmental regulations, but also to improve habitat conditions for all organisms in the ecosystem.

Does SHRP identify research priorities as well as action priorities?

Yes. Using the assessment tools described in SHRP will help the planning entities identify and prioritize both information needs (and associated research priorities) and necessary restoration activities. In addition, individual restoration activities should be treated as research projects to determine their effectiveness.

What is the relationship of SHRP to quantitative salmon recovery goals set forth in biological delisting criteria?

The recovery goals (biological delisting criteria) will be determined by NOAA Fisheries, based on guidance from the TRTs for each Evolutionary Significant Unit (ESU), and will differ based on local conditions in each ESU. These targets will be based on scientific data assessed by each TRT, and the SHRP document is intended to assist with such assessments. The restoration actions described in SHRP are designed to increase the viability of salmonid populations (of which there may be several in a given ESU). Precise estimates of the number of fish that will be recovered by certain actions cannot be predicted, but qualitative estimates can be made about which actions are likely to have the most impact on salmon populations.

How does the information provided in SHRP relate to different geographic areas in the Pacific Northwest?

Recovery planning will involve activities specific to the region in which the targeted species occur. SHRP discusses how ecosystem processes, and thus recovery activities and activity prioritization, might differ among different ecoregions of the Pacific Northwest (Levels II and III as defined by the Environmental Protection Agency).

How do spatial and temporal variation affect recovery planning?

Ecosystem processes vary in space and time. An appendix to SHRP discusses potential effects of scale on results and suggests that a recovery plan should incorporate assessments and analyses at multiple scales to be most effective.

How can sound decisions be made during recovery planning despite uncertainty?

Uncertainty associated with data collection, analyses, and interpretation (as well as natural variation) can affect the quality of decision-making. SHRP suggests ways to acknowledge and manage uncertainty throughout the recovery process to ensure that decisions are well-informed.

Will following the SHRP guidance result in a final habitat recovery plan?

The SHRP guidance is meant to assist in the development of habitat components of an initial recovery plan. Additional information will continue to be collected from ongoing research and monitoring of restoration actions. As this additional information is gathered, the plan will likely be revised. Thus, SHRP can help with prioritization of interim recovery actions pertaining to habitat, and with development of revised prioritized lists that will become part of a final recovery plan.

Can the assessments described in SHRP be useful in preventing future habitat degradation?

Yes. The information generated from the habitat assessments described in SHRP can be used to elucidate impacts of various land use activities on ecosystem process and habitat conditions. This information should allow land-use planners to ensure that future activities are less likely to result in the future degradation of habitat used by salmon and other species.

2) CHINOOK SALMON LIFE-CYCLE MODEL

Abstract, table of parameter estimates, main results figure, and references for the manuscript are presented below. The full paper was submitted for publication in November 2002.

Habitat-specific population dynamics of ocean-type chinook salmon (*Oncorhynchus tshawytscha*) in Puget Sound

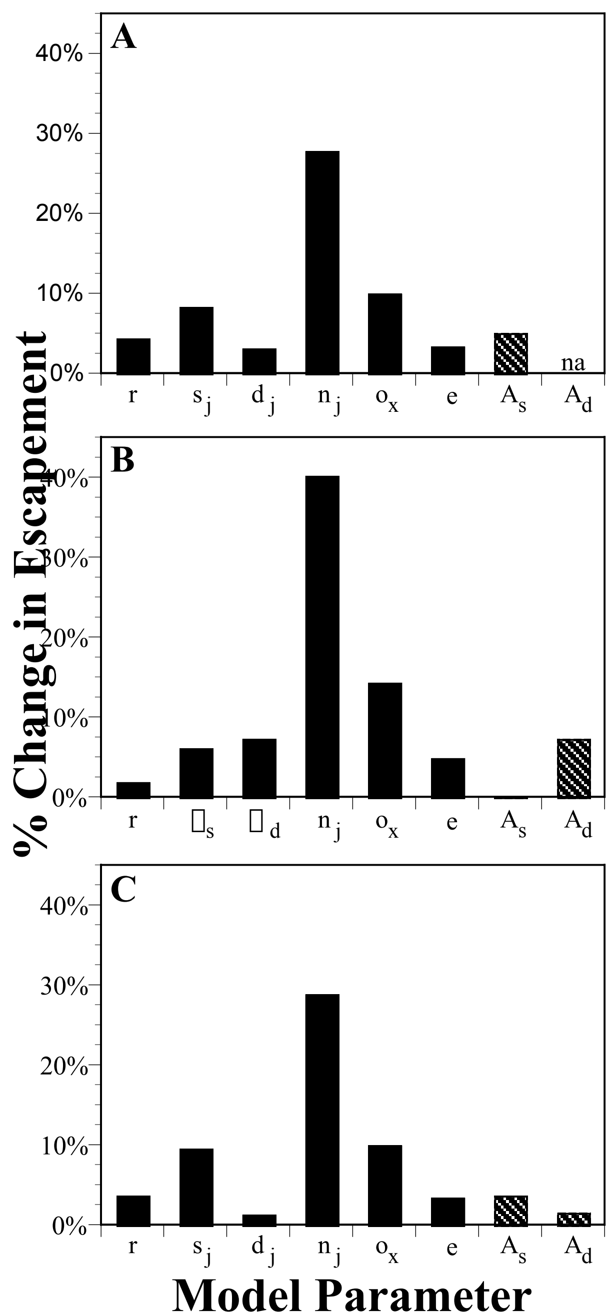
By Correigh Greene and Tim Beechie

Restoring salmon populations depends on our ability to predict the consequences of improving aquatic habitats used by salmon. To examine the relative importance of different aquatic habitats used by chinook salmon in Puget sound, we constructed a watershed-scale Leslie matrix model that specifies residency and survival in spawning nests (redds), streams, tidal deltas, nearshore habitats, and the ocean (Table 1). We compared the relative importance of different habitats under three density-dependent scenarios: 2) density-independent survival with a spawning capacity, 2) density-dependent survival within streams and delta, and 3) density-dependent movement among streams, delta, and nearshore (Fig. 1). In all scenarios, population dynamics were most sensitive to changes in nearshore and ocean mortality. Sensitivity to changes in freshwater and delta habitats depended upon the scenario: under all scenarios but the second, escapement was more sensitive to changes in stream survival and area, while escapement under the second scenario was more affected by changes in delta productivity and area. These findings indicate that nearshore habitat relationships may play significant roles for salmon populations, and that the relative importance of stream and tidal delta habitats will depend upon the form of density dependence influencing salmon stocks.

Table. Model parameters and parameter estimates used in the model.

Parameter	Description	Value	Reference
r	Monthly redd survival	0.855	Wasserman et al. 1984, Fast et al. 1985, Fast et al. 1986
s_j	Monthly juvenile stream survival	0.553	Wetherall 1971
d_j	Monthly juvenile tidal delta survival	0.619	See text
n_j	Monthly juvenile nearshore survival	0.442	See text
Tr	Redd residency (months)	5	Alderdice and Velsen 1978, Williams et al. 1975
Ts	Stream residency (months)	2	Williams et al. 1975
Td	Tidal delta residency (months)	1	Healey 1980
tn	Nearshore residency (months)	4	Williams et al. 1975
o_2, o_3, o_4, o_5	Age-specific annual ocean survival	0.6, 0.7, 0.8, 0.9	Chinook Technical Committee 2001
a_3, a_4, a_5	Age-specific breeding propensity	0.112, 0.532, 1.0	Ratner et al. 1997
m_3, m_4, m_5	Age-specific fecundity	4848, 5710, 6664	E. Beamer, pers. comm.[1]
E	Escapement rate	0.6	Puget Sound TRT, pers. comm.[2]
$\square_s$	Stream productivity	0.599	See text
k_s	Stream capacity	4800	See text
$\square_d$	Tidal delta productivity	3.22	See text
k_d	Tidal delta capacity	10000	See text
A_s	Stream area (ha)	5000	See text
A_d	Tidal delta area (ha)	1000	See text

Figure. Sensitivity analysis of escapement to changes in model parameters when population dynamics are influenced by A) a hockey stick scenario (dynamics are density independent below a spawning capacity), B) density-dependent survival in the stream and tidal delta, and C) density-dependent movement through the stream and tidal delta. Each bar represents a percentage change in escapement resulting from a 5% change in a particular model parameter. Black bars are survival parameters, and hatched bars are habitat area parameters.



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3) SALMONID WATERSHED ANALYSIS MODEL (SWAM)

The following is a manuscript accepted for publication in UPDATE, a publication of the School of Natural Resources and the Environment, University of Michigan. The article describes completed SWAM analyses and their potential uses in recovery planning. Also included here are summaries of the following 1) BPA-funded SWAM analyses, 2) abstracts of an accepted manuscript and manuscripts in review, and 3) two figures of interest that illustrate the spatial extent of completed SWAM analyses and potential map products from SWAM analyses.

NOTE: Since the submission of this article the name of the NOAA Technical Memorandum "Salmon Habitat in Recovery Planning" was changed from "Ecosystem recovery planning for listed salmon: an integrated assessment approach for salmon habitat".

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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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 (Figure 1). Furthermore, it is estimated that scores of historic populations have become extinct (NRC, 1996). 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.

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 ESUs, which are composed of one or more populations. 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.

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.

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 (Figure 5). 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 (Figure 6).

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

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.

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.

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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.

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						
Δ Alpine Vegetation	**X**				**X**	
Δ Open Water		**X**				
Δ Ponderosa Pine		**X**				
Δ 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

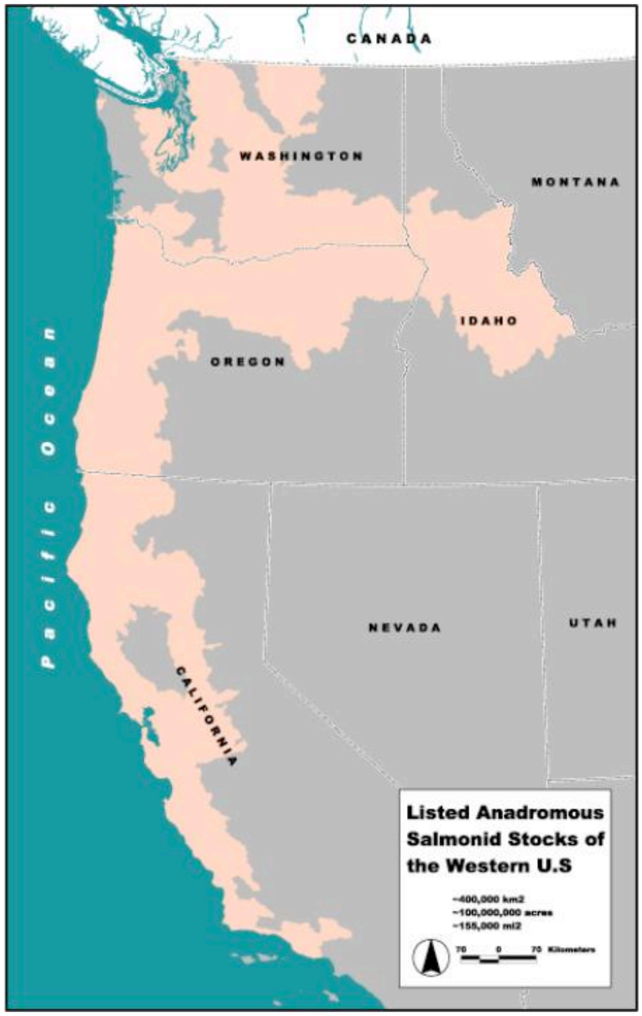

Figure 1. Map of total area occupied by ESA listed anadromous salmonids. Map compiled from various maps of ESA listed anadromous salmonid species (NMFS 2002). These source maps depict major river basins within the current known range of the species/ESU, and are for general reference only. The various 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.

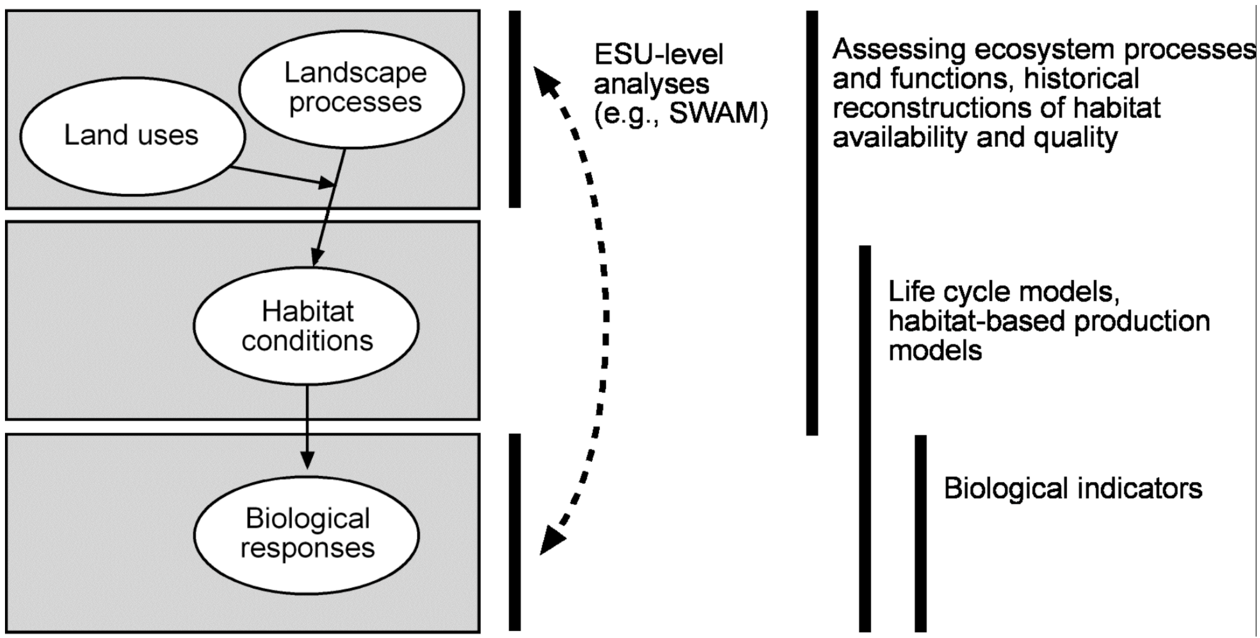

Figure 2. Schematic diagram of linkages among landscape processes, land use, in-stream habitat, and biological responses. For ESU-wide analyses of land use effects on salmon populations, landscape and land use factors can be correlated with indicators of population performance (e.g., SWAM) (Modified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

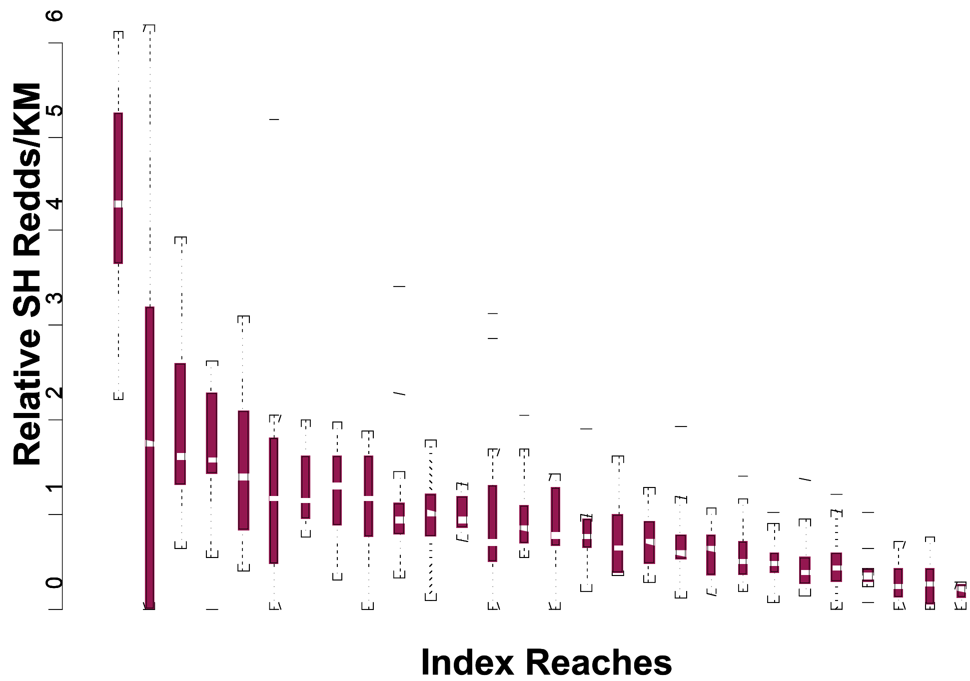

Figure 3: Distribution of steelhead redds by index reach from 1979-1999 in the Santiam, Calapooia, and Molalla watersheds within the Willamette River basin. Relative number of steelhead redds was calculated as the fraction of redd density observed in a particular year within a particular reach divided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

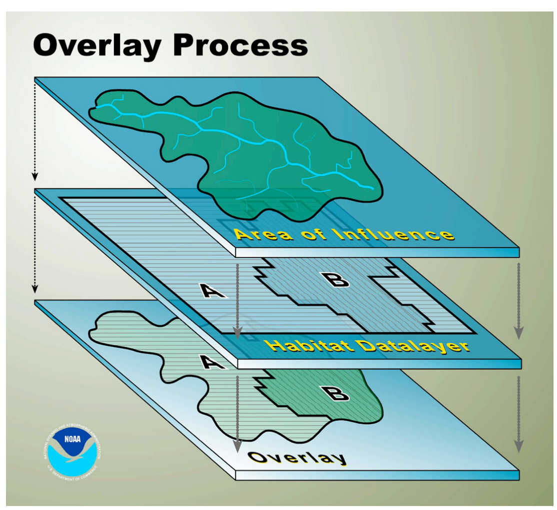

Figure 4: Schematic representation of GIS datalayer overlay process used to determine the fraction or percent area covered by various habitat categories in a given watershed associated with a given index reach.

SWAM RELATED PAPERS AND ANALYSES

The influence of scale on salmon habitat restoration priorities (Salmon River Basin)

Blake E. Feist, E. Ashley Steel, George R. Pess, Robert E. Bilby

In Review

Abstract: Habitat loss and alteration is the leading cause of species' declines worldwide, therefore, habitat restoration and protection is a prominent conservation strategy. Despite obvious connections between habitat and threatened or endangered species, conservationists have been hard pressed to explicitly link abundance or population health with habitat attributes. Given that habitat relationships with species are often characterized at a spatial scale that does not account for the functional relationships between habitat and populations, it's not surprising that the habitat-population conundrum persists. In order to explore the influence of spatial scale on the apparent relationship between habitat and populations, we examined the relationship between GIS based habitat data and spring/summer chinook salmon (*Oncorhynchus tshawytscha*) redd (spawning nests built by females) densities in the Salmon River basin, Idaho, at two very different spatial scales: stream reach and watershed. Redd density was strongly correlated with climate, geology, wetlands, and terrain. However, our stream reach scale models provided poor predictive power compared with the watershed scale models. Based on these results, we conclude that our perception of which habitat attributes were important was clearly a function of our scale of observation, and that restoration efforts should focus on conditions at the watershed or landscape scale when attempting to do local or reach scale restoration projects.

Landscape characteristics, land use, and coho salmon (*Oncorhynchus kisutch*) abundance, Snohomish River, Wash., U.S.A.

George R. Pess, David R. Montgomery, E. Ashley Steel, Robert E. Bilby, Blake E. Feist, and Harvey M. Greenberg

Canadian Journal of Fisheries and Aquatic Science 59(4): 613-623 (2002)

Abstract: We used temporally consistent patterns in the spatial distribution of returning adult coho salmon (*Oncorhynchus kisutch*) to explore relationships between salmon abundance, landscape characteristics, and land use patterns in the Snohomish River watershed, Wash. The proportion of total adult coho salmon abundance supported by a specific stream reach was consistent among years, even though interannual adult coho salmon abundance varied substantially. Wetland occurrence, local geology, stream gradient, and land use were significantly correlated with adult coho salmon abundance. Median adult coho salmon densities in forest-dominated areas were 1.5–3.5 times the densities in rural, urban, and agricultural areas. Relationships between these habitat characteristics and adult coho salmon abundance were consistent over time. Spatially explicit statistical models that included these habitat variables explained almost half of the variation in the annual distribution of adult coho salmon. Our analysis indicates that such models can be used to identify and prioritize freshwater areas for protection and restoration.

Large-scale habitat models to understand steelhead (Oncorhynchus mykiss) distribution and prioritize barrier removals in the Willamette basin, OR, U.S.A.

E. Ashley Steel, Blake E. Feist, David Jensen, George R. Pess, Mindi Sheer, Jody Brauner, Robert E. Bilby

In Review

We use linear mixed models to predict steelhead redd density from geology, land-use, and climate variables in 4 watersheds of the Willamette River basin, Oregon and use the model to estimate potential steelhead redd density and abundance above barriers to passage within the study watersheds. Our approach allows us to model the temporal correlation between annual fish observations at the same site while extracting patterns of relative redd density that are consistent among years with varying strengths of steelhead returns. Landscape variables included in the set of best models were alluvium, hillslope > 6%, landslide-derived geology, young (<40yrs) forest, shrub vegetation, agricultural land-use, and mafic volcanic geology. We used the above model to predict redd density (redds per kilometer) upstream of 111 probable migration barriers and the potential relative number of redds behind each barrier as well as several metrics of uncertainty. The modeled prioritization scheme based on redd density selects only a subset of the high priority barriers as identified using stream length alone and illustrates clear trade-offs between high predicted redd densities and high levels of uncertainty.

Status Report of BPA-Funded SWAM Analyses in the Columbia River Basin

Blake Feist and Ashley Steel

As of December 2002, all spatial and statistical analyses in the John Day, Wenatchee, and Yakima subbasins (Figure 5) were completed. The analyses were conducted according to the approach outlined in the UPDATE article above. Due to differences in available data between subbasins, there were slight variations in the analytical approach to each subbasin analyzed. These minor differences are not described in the Status report.

DATA USE D

⇛ *Redd Counts* – Redd count data were obtained from STREAMNET initially, and supplemental data were obtained from other sources as necessary (including the NWFSC spawner database). To our knowledge, we worked with comprehensive datasets. All index reaches were mapped to either 1:24k or 1:100k USGS stream networks.

⇛ *Geospatial* – Most geospatial datalayers were readily available from previous SWAM analyses done in the Willamette and Salmon River basins (see abstracts above). However, the following had to be generated or extensively manipulated: 1:24k stream network and stream junctions for the John Day; 10 m DEM mosaicing and error correcting; watershed flow accumulations; and explicit maps of index reach segments.

ANALYSIS

⇛ *Spatial* – The NWFSC Data Management Team, created a tool in ArcView that greatly accelerated running the spatial component of SWAM. This tool also improved accuracy and reduced the likelihood of errors. Spatial analyses were completed in three subbasins for chinook, and also for steelhead in one of the subbasins (see Table below, and attached map). Analyses were run at three areas of influence or spatial scales: reach (500 m buffer around index reach); HUC 6 buffer (HUC 6 catchments directly contacting index reach); and watershed (entire catchment flowing into given index reach). Output from the spatial overlays at the three different scales, with the various GIS habitat datalayers, was summarized in a table, created using the aforementioned ArcView tool. This output was then used for the statistical portion of the modeling.

⇛ *Statistics* – Statistical analyses have been completed for each of the four SWAM runs described (Table 1). We applied a mixed models approach at each of the three areas of influence described above and for each of the four SWAM runs independently. The mixed models approach allows for temporally correlated observations within a site and makes use of all the available data. It was not necessary to average redd counts within a site or ignore sites with missing data. We had access to excellent habitat data, which enabled several new variables (not available for earlier SWAM runs) that describe habitat change. For each area of influence and each run, a set of best models was developed using a modified all subsets routine. All models were tested to check that no one observation was driving the results using Cook's distance, modified for use with mixed models. Each potential model has also been tested for prediction accuracy using a leave-one-out cross-validation approach. The set of best models was selected based on statistical significance of the predictors, model fit using the Bayesian information criteria (BIC), correlations between habitat variables in the model, robustness of the model, and predictive success in the cross-validation procedure.

RESULTS

⇛ *Chinook salmon in the Wenatchee and John Day Rivers* – For each of the two SWAM runs, there were only 6 index sites. Model fitting was therefore limited. The best results were achieved for the watershed area of influence. The density of dams and channel slope were the most useful variables for predicting the distribution of chinook salmon redds in the Wenatchee River. Cattle grazing allotments were the best predictor of chinook salmon redd density in the John Day River.

⇛ *Chinook salmon in the Yakima River and steelhead in the John Day River* – There were large numbers of index sites available for both of these SWAM runs and the modeling was successful for all three areas of influence. Correlations between observed and predicted redd densities were often as high as 0.9. Because there were a high number of good models, we selected a set of best models for each run and area of influence and averaged the predictions from that set of models. We used that same approach in the Salmon and Willamette basins. Overall, it appears that channel slope, vegetation, and dam density are strong predictors of chinook redd density on the Yakima River. Hillslope and surrounding topography, precipitation, and vegetation are among the best predictors of steelhead redd density on the John Day river.

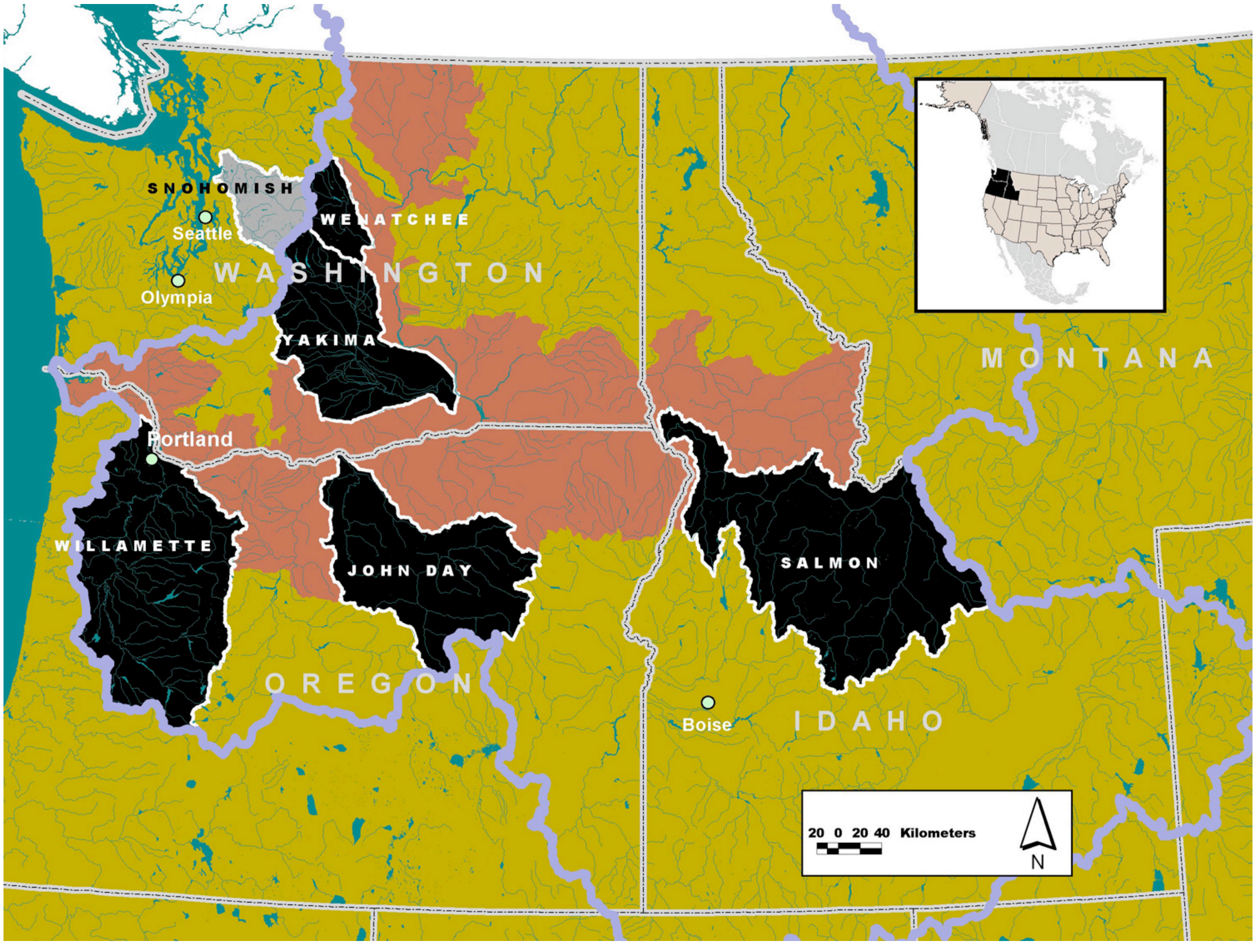

Figure 5. Subbasins in the Columbia River basin where SWAM analyses have been condcuted for BPA. Red represents other areas in the anadromous zone of the Columbia River basin where SWAM analyses have not been initiated. The gray area represents a basin outside of the Columbia (Snohomish) where SWAM analyses have been completed.

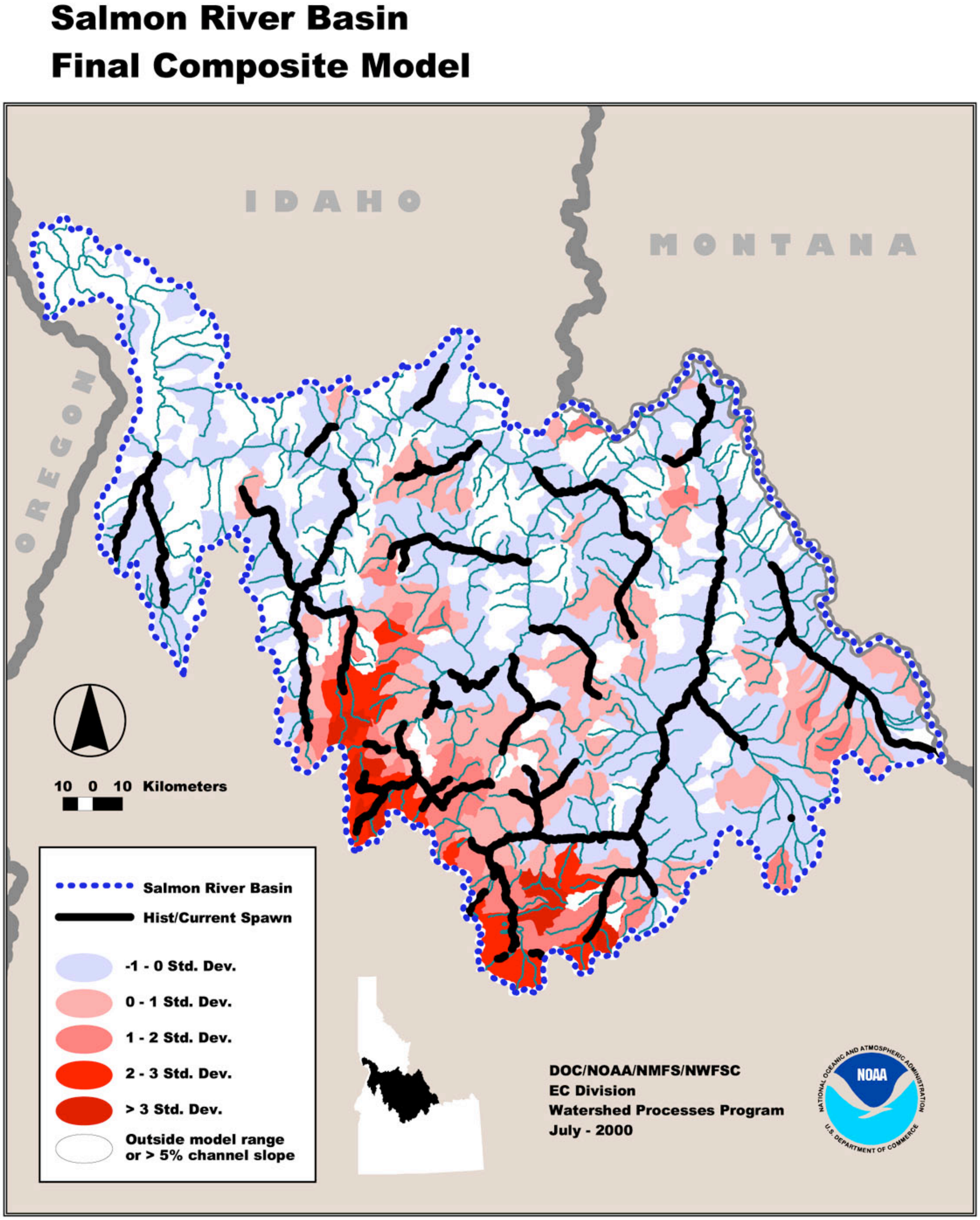

Figure 6. Predictive composite mixed spatial model of potential spring/summer chinook spawner densities in the Salmon River basin, Idaho. Predicted densities are at 6th field hydrologic unit scale, and are expressed as standard deviations above or below the mean.