GIS-Based Evaluation of Salmon Habitat in the Pacific Northwest

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Abstract
Categorization of 164,083 kilometres of stream length has provided the first quantitative measure of the extent and location of potential salmon stream habitat throughout western Washington State. Reach slope and forest seral stage provided a coarse indicator of channel condition across the region. Reach-average slopes calculated for individual stream reaches using 30-metre digital elevation model (DEM) data, correctly identified low-gradient (less than 4.0 percent slope) response reaches that typically provide habitat for anadromous salmon with an accuracy of 96 percent (omission and commission error rates of 24.0 and 4.0 percent, respectively). Almost one-quarter (23.2 percent) of all stream length categorized consisted of response reaches, of which only 8.7 percent were associated with late-seral and 20.7 percent with mid-seral forest stages. Approximately 70 percent of the total stream length potentially providing anadromous salmon habitat is associated with non-forested and early-seral stage forests. GIS-based analytical techniques provided a rapid, objective, and cost-effective tool to assist in prioritizing locations of salmon habitat preservation and restoration efforts in the Pacific Northwest.

Introduction
Dramatic declines in Pacific Northwest (PNW) salmon stocks have been associated with land-use induced freshwater habitat losses (Nehlsen *et al.*, 1991). Substantial resources are being directed towards the restoration of stream habitats in efforts to maintain and/or restore wild salmon stocks in the PNW, yet there is no common scientific framework for guiding the prioritization of where and how salmon habitat preservation and restoration activities should occur. GIS-based analysis can provide a systematic tool for targeting restoration opportunities by rapidly characterizing potential salmon habitat over large geographic regions and by providing baseline data for development of habitat restoration strategies. When integrated, data on stream channels, riparian habitat, and watershed characteristics provide a powerful tool for the development of watershed restoration and management strategies (Delong and Brusven, 1991).

Previous efforts to prioritize salmon habitat preservation and restoration opportunities on state and federal lands in Oregon (Bradbury *et al.*, 1995) and Washington (Oman and Palensky, 1995) have met with some success, but problems associated with data availability over large geographic regions have limited applications. The objectives of this study were to (a) develop a rapid, cost-effective, and objective analytical tool to support prioritization of specific subbasins and watersheds for salmon habitat preservation and restoration opportunities; (b) investigate the correspondence between forest seral stage and large woody debris (LWD) recruitment and associated pool-riffle stream bed morphologies; (c) illustrate the creation of integrated baseline data to support watershed analyses and the development of preservation and restoration strategies; and (d) explore the use of such data to facilitate the communication of scientific information to decision-makers and the public.

Approach
Classification schemes impose order on a system for some particular purpose. Stream channel classifications, for example, provide a means to evaluate and assess the current condition and potential response of channel systems to disturbance (natural and anthropogenic). Identification of functionally distinct channel types can also target field work on stream reaches of particular interest and provide a reference frame for communication between multi-disciplinary groups evaluating habitat conditions. No channel classification is ideal for all purposes, and the approach adopted should reflect the goals to which a classification will be applied. Our project needed to identify the likely location and quality of salmon habitat from existing regional data. Numerous channel classification systems rely on the integration of physical variables such as channel slope, channel morphology, and channel pattern (Paustian *et al.*, 1992; Montgomery and Buffington, 1993; Rosgen, 1994).

Several existing channel classifications can be applied to PNW streams. Paustian *et al.* (1992), for example, broadly classify stream channels according to fluvial process groups (i.e., estuarine, palustrine, alluvial fan, etc.). Rosgen (1994) combined channel slope, cross-section morphology, and planview morphologic attributes to classify stream reaches into general categories. Rosgen (1994) then includes channel entrenchment, width-to-depth ratio, sinuosity, slope, and bed material to further refine stream type categories. Of these attributes, only channel slope is readily determined from typical digital data available over broad regions. Moreover, neither approach allows modification of channel type due to the influence of large woody debris contributed from stream-side forests, which can be a primary influence on the morphology of stream channels in the Pacific Northwest (Swanson and Lien-

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kaemper, 1978; Keller and Swanson, 1979; Montgomery *et al.*, 1995; Abbe and Montgomery, 1996).

For this study, we selected the classification system of Montgomery and Buffington (1993) which broadly stratifies channel morphology and allows for adjustment of channel type due to morphologic influences of LWD, and can be applied over large areas on the basis of correlations with reach average slope. At the reach level of classification, channel morphology is controlled by hydraulic discharge, sediment supply, and external influences such as LWD. The classification identifies distinct alluvial bed morphologies (e.g., pool-riffle, plane-bed, step-pool), and the influence of large woody debris on "forcing" stream morphology is designated by modifiers added to a particular reach label (e.g., forced pool-riffle). These specific channel morphologies can be generalized into source, transport, and response reaches (Montgomery and Buffington, 1993). In mountain drainage basins, source reaches tend to be debris-flow-prone colluvial channels that function as headwater sources of sediment to downstream reaches. Transport reaches tend to be step-pool and cascade morphology reaches that rapidly convey increased sediment loads to lower-gradient downstream channels. Response reaches are pool-riffle and plane-bed channels that can exhibit dramatic morphologic response to increased sediment loads. Channel reach slope (S) generally correlates with reach morphology, particularly at the coarse level distinctions of source ($S \geq 0.20$), transport ($0.04 \leq S < 0.20$), and response reaches ($S < 0.04$).

Among response reaches, several morphologic types may occur. Channels with slopes between 0.001 and 0.01 typically exhibit pool-riffle morphology regardless of LWD loading levels, whereas channels with slopes between 0.01 and 0.02 are LWD dependent: at low LWD loading, these reaches typically have either a pool-riffle or plane-bed (i.e., riffle-dominated) morphology, whereas at higher LWD loading, LWD pieces and LWD jams force the formation of pools; hence, the name forced pool-riffle channel. Channels in the 0.02- to 0.04-slope range typically exhibit plane-bed or forced pool-riffle morphologies, depending upon LWD loading (Montgomery and Buffington, 1997). Channels with slopes above 0.04 typically exhibit step-pool or cascade morphologies. Of these channel types, salmonid species appear to strongly prefer pool-riffle and forced pool-riffle channels.

Identification of response reaches provides a simple method for identification of potential salmon habitat, as the zone of anadromous fish use typically is restricted to these low-gradient reaches in Pacific Northwest watersheds (Montgomery, 1994). Also, the age class of stream-side forests can indicate the potential for a source of abundant large woody debris to stream channels. Channel slope can be readily determined from digital elevation models. We coupled this coarse slope-based classification of channel types with remote sensing data on the associated seral stage of the stream-side forest to generate a regional GIS-driven classification of potential salmonid habitat locations and quality. This approach, however, simply provides an indication of the likely channel type and a general sense of the likely woody debris loading. Channel slopes determined from digital elevation models (DEMs) and wood loadings derived from forest seral-stage correlations can be misleading due to (a) poor topographic representation in the DEM at the scale of channels; (b) the natural overlap and range in slope for different channel types; (c) variations in channel type due to local controls; and (d) differences between in-channel LWD loading and riparian forest conditions due to removal of LWD from channels flowing through mid- to late-seral stage forests or clear cutting of stream-side forests without removal of in-channel LWD. In spite of these caveats, the simple classification based on general channel type and riparian forest seral stage provides a direct screening tool for identifying likely sites of low- and high-quality salmon habitat.

We infer that pool abundance correlates with overall habitat quality, and that LWD loading is an important factor in determining habitat quality in response reaches. Assuming that riparian forest conditions correlate with increased LWD loading, it follows that the condition of the adjacent riparian forest would correlate with channel type over the slope range of approximately 0.01 to 0.04, with older forests having higher potential for LWD loading and a higher probability of being forced pool-riffle reaches (high quality habitat). Conversely, reaches with young forests or no forest along the channel have a higher probability of being a plane-bed reach (poor quality habitat).

Application of our results to prioritize specific sub-basins and watersheds for salmon habitat protection and restoration efforts is based on three major assumptions: (1) salmon stocks are adapted to local environmental conditions; (2) preservation of "natural" conditions will benefit multiple salmonid species; and (3) a general categorization of channels adequately describes key habitat elements for multiple salmonid species. The first two assumptions are more completely explained by Peterson *et al.* (1992) and Beechie *et al.* (1996). The third assumption is supported by limited data showing that several species and life history stages select the same two channel types over others (E. Beamer, unpublished data). These preferences appear to be related to factors such as pool area and depth, cover complexity, and the quality of spawning gravels.

Methods

Watershed screening was performed at both the sub-basin (>450 km^2) and watershed (<260 km^2) scales to identify probable high quality and degraded locations in western Washington State. For the purposes of this study, sub-basins correspond to Washington Department of Natural Resources (WDNR) Water Resource Inventory Areas (WRIAs) and watersheds correspond to WDNR Watershed Administrative Units (WAUs). The multiple analytical scales provide comparative evaluations of potential salmon habitat across large geographic regions (e.g., western Washington State) or for evaluations across watersheds within an individual sub-basin. Data outputs were summarized by WAU, which typically comprise 120 to 260 km^2. WAUs are subunits within larger sub-basins (WRIA) that range from 450 to 6,500 km^2 in western Washington State. The GIS-based predictions of potential habitat locations serve to extend the spatial extent of field observations across the entire study area.

Data Sources

Ideally, all spatial data sources should be derived and used at a scale commensurate with the ecological processes of interest. For this project, the appropriate source data scale for watershed analysis and management activities across the western Washington project area is 1:24,000 and larger to accurately resolve the location of salmonid stream habitat. However, large-scale digital data sets such as vegetation cover and land ownership were not available over the project area. At the expense of spatial resolution, some coarser resolution data sets were used (Table 1).

Two sources of digital hydrographic data were available: (1) the U.S. Environmental Protection Agency's (EPA's) 1:100,000-scale "river reach files" and (2) 1:24,000-scale hydrography provided by the WDNR. The river reach files have the advantage of unique identifiers for all stream reach locations. Nonetheless, superior mapping resolution associated with the 1:24,000-scale hydrography data was considered a better match for the needs of this study because most field observations and stream habitat measurements were recorded

TABLE 1. STUDY DATA SETS AND CORRESPONDING SCALE, FORMATS, AND SOURCE DESCRIPTION.

Data	Scale	Format	Description
DEM	1:24,000	raster	7.5-minute; 30-metre cell; Levels 1 & 2.
Hydrography	1:24,000	vector	Compiled from USGS 7.5-minute quads & aerial photography
Transportation	1:24,000	vector	Compiled from USGS 7.5-minute quads & aerial photography
WAU Boundaries	1:100,000	vector	Variable accuracy due to multiple regional mapping efforts.
WRIA Boundaries	1:24,000 1:62,500	vector	Boundaries developed by state natural resource agencies in cooperation with the USGS.
Forest Vegetation Seral Stage	~1:100,000	vector/raster	Landsat Thematic Mapper (TM)-derived forest cover.
Land Use/Land Cover	1:250,000	raster	Non-forested lands (ag./urban/etc.) from USGS Land Use/Land Cover.
Validation Data	1:24,000 1:12,000	hardcopy map/pt. data and tabular data.	Field observations.
Land Ownership	1:100,000	vector	Public land ownership
Landsat TM	~1:100,000	raster	Terrain-corrected imagery ± 15 metres

at scales of 1:24,000 and larger, and absolute stream orientation was critical for subsequent spatial data analyses across multiple thematic data layers.

The only available data source for hydrologic unit delineations at both the sub-basin and watershed scales for western Washington State was the WRIA and WAU coverages. WRIA boundaries were compiled under multiple efforts using variable 1:24,000- to 1:100,000-scale maps, and WAUs were generally compiled using 1:100,000-scale base maps (WDNR, 1994). Incongruities between the WAU boundary delineations and the larger scale hydrography were common. For example, along wide river mainstems WAU boundaries were not always in agreement with river mainstems, especially as river shape became more sinuous in the 1:24,000-scale hydrography data.

Total road length and road density were important attributes used in the assessment of potential habitat quality at the WAU scale of analysis. Transportation data were available for the project area at 1:100,000 and 1:24,000 scales. The 1:24,000-scale data provided the most complete depiction of primary, secondary, and logging roads.

Available source scales for digital elevation data of western Washington were the 1-degree or three-arc-second (~85-metre) data and the 7.5-minute (30-metre) DEM data constructed from 1:24,000-scale maps. Given the need to assess channel slope as accurately as possible for this project, the larger scale data provided the best estimate of stream slope over relatively short stream reaches. The slope of stream arcs was measured over an arc distance of 150 metres. For this purpose, the 30-metre cell size of the 1:24,000-scale elevation models provided superior topographic resolution.

Forest-cover data were originally derived from 1988 Landsat 5 TM data (PMR, 1993) and updated with 1991 and 1993 TM data using image differencing followed by level slicing to identify new clear cuts (Collins, 1996). The nominal data resolution of 30 metres was interpolated to 25 metres during the terrain correction process. Standard digital image interpretation techniques were then applied to generate the forest-cover data (PMR, 1993). Forest cover was broadly categorized into four classes based on forest type and age class (Table 2). The overall thematic accuracy of the 1988 TM-based land-cover categorization was 92 percent (PMR, 1993).

The non-forest land cover and most surface water features were derived from 1:250,000-scale U.S. Geological Survey land-cover/land-use data. The data were overlaid on the forest-cover classification to discriminate non-forest lands, such as agriculture and urban areas, from forest lands (PMR, 1993). Thus, the final land-cover layer contained a mixture of source scales ranging from approximately 1:100,000 to 1:250,000.

Field data used to validate stream channel type prediction were provided as part of an on-going salmon habitat inventory and management effort. Inventory efforts focused primarily on streams with relatively low channel slopes (<4.0 percent) and were compiled on 1:12,000-scale orthophotos. Channel slope data were collected using either transit, hand level, or clinometer measurements.

Data Quality and Error Propagation

Errors associated with remote sensing and GIS data acquisition, processing, analysis, data conversion(s), and final data

TABLE 2. STUDY LAND-COVER CATEGORIES DERIVED FROM LANDSAT 5 THEMATIC MAPPER (TM) DATA (PMR, 1993; WDNR, 1994).

Class 1
Late Seral Stage
Coniferous crown cover greater than 70%.
More than 10% crown cover in trees greater than or equal to 21 inches diameter breast height (dbh).

Class 2
Mid-Seral Stage
Coniferous crown cover greater than 70%.
Less than 10% crown cover in trees greater than or equal to 21 inches dbh.

Class 3
Early Seral Stage
Coniferous crown cover greater than or equal to 10% and less than 70%. Less than 75% of total crown cover in hardwood tree/shrub cover.

Class 4
Other Lands in Forested Areas
Less than 10% coniferous crown over (can contain hardwood tree/shrub cover; cleared forest land, etc.).

Class 5
Surface Water
Lakes, large rivers, and other water bodies.

Class 15
Non-Forest Lands
Urban, agriculture, rangeland, barren, glaciers.

Note:
(1) Forest cover derived from Landsat Thematic Mapper (TM) satellite imagery.
(2) Class 5 derived from Landsat TM and 1:250,000-scale USGS Land-Use/Land-Cover data.
(3) Class 15 derived from 1:250,000-scale USGS Land-Use/Land-Cover data.

presentation can significantly impact the confidence associated with resultant products and, thus, influence their utility in the decision making process. It was not feasible within the scope of this project to explicitly measure discrete error sources and calculate an error propagation budget. Thus, channel type prediction was the only accuracy assessment performed. Channel type accuracy reflects key input data limitations and processing errors. The final GIS data products may give the appearance of uniform thematic accuracy; however, there may be significant variability across specific geographic locations based on the least accurate input data source (Lunetta *et al.*, 1991).

Spatial Data Preprocessing

Data Format Conversions

Data conversion from vector to raster can cause undesirable shifts of objects in the output raster data as well as changes in area and shape (Congalton and Schallert, 1992). This error source was minimized as much as possible by maintaining data in their native format and thus performing limited data conversions. Raster-to-vector conversions were not performed as part of the project; however, the forest-cover data, originally processed from Landsat TM digital imagery, were converted to a vector representation prior to processing (PMR, 1993). Also, all single-line hydrographic arcs underwent vector-to-raster conversion to optimize stream buffer calculations (see Stream Buffer Vegetation Tabulation).

Data Generalization

With the exception of the land-cover layer, most data sources were not generalized. The Non-Forest (class 15) and Surface Water (class 5) classes listed in Table 2 were originally compiled under USGS mapping guidelines. The land-use and land-cover data were interpreted from aerial photography at a scale of 1:60,000 or larger and compiled on 1:250,000-scale topographic maps (USDI, 1993). The guidelines specify a 4.0-hectare minimum mapping unit for urban/built-up lands, surface water, and some agricultural areas. The minimum mapping unit for cropland, pasture, and barren lands is 16.2 hectares. As noted above, the non-forest and surface water data were overlaid on the seral stage coverage to create a combined land-cover layer. This layer was subsequently converted to vector format.

Prior to conversion of the land-cover data to vector format, a filtering procedure was performed on the raster data coverage to merge polygons smaller than nine pixels into adjacent polygons using a simple majority rule decision criteria. Subsequently, vector polygons smaller than the minimum mapping unit size of 2.0 or 4.0 hectares (depending on adjacent land-cover type) were removed (PMR, 1993). Thus, stream-bank forest land cover was not accurately represented for patch sizes of less than 4.0 hectares.

Geometric Rectification

GIS processing of multiple data layers requires that all layers reside in a common map projection. A common projection was determined prior to processing based upon possible error sources and processing efficiency. Because project outputs were assumed to be most sensitive to elevation errors, the DEM data were maintained in their native Universal Transverse Mercator (UTM) projection. Changing their projection would have introduced additional error and increased data processing time due to interpolation of cell values because both the DEM and vector land-cover data existed in UTM space. Therefore, all input data not in UTM space were projected to the UTM space of the DEMs and land-cover data.

DEM Processing

ARC/GRID analytical routines were used to mosaic 7.5-minute DEMs for each WRIA. Once a grid was created for a WRIA, it was next processed to remove "sinks" (sinks are cells with an undefined flow direction). The processed DEM was then used in stream channel slope calculations. Additional DEM processing was performed to create a slope grid for each WRIA for use in summary statistics compilation. The slope grid was then recoded into three landscape slope classes: (a) Class 1, 0 to 29 percent; (b) Class 2, 30 to 65 percent; and (c) Class 3, greater than 65 percent.

Preparation of Hydrography

The 1:24,000-scale hydrography data, originally tiled by township, were appended and clipped to the respective WRIA boundary. Stream direction was set to point upstream. Stream percent slope was then computed from DEM values for each arc. Start and end elevation and slope were written to the hydrography coverage arc attribute table.

Forest Seral Stage

This coverage was checked for positional errors and logical consistency by overlaying it with the ancillary geocoded TM data to serve as a base map. The absolute positional accuracy of the TM base map was plus or minus 15 metres (Table 1). If positional errors were found, then a simple x,y shift was performed to improve geometric fidelity. Thematic inconsistencies between the vegetation layer and the TM data were not reviewed. Ideally, obvious errors, such as urban encroachment on forest lands, would have been corrected through editing procedures using the TM data as a validation data source. However, resource limitations precluded the inclusion of such editing.

Spatial Data Analysis

Each WRIA was processed individually using identical protocols. The first step was to compile all data inputs for processing, followed by creation of summary data statistics, hardcopy maps, and graphics. Summary statistics and data graphics were generated for both the WRIA and WAU hydrographic units. Additionally, validation procedures were performed using data from nine WAUs (Bacon Creek, Illabot, Jackman, Nookachamps, Finney, Hansen Creek, Gilligan, Mt. Baker, and Alder) located within the Upper and Lower Skagit River WRIAs. The categorization of stream channel types was accomplished using an automated procedure to calculate slope for individual stream reaches.

The sampling procedure was initiated at the low elevation end of the arc, and measured upstream the specified sampling distance of 150 metres. If a slope less than 4 percent is found over the sample distance, then the arc ID number and UTM coordinate at the end of the sample distance are stored in a file. Upon locating a slope less than 4 percent, the procedure then moves upstream along the arc another sample distance and measures the slope. The process is repeated if a slope less than 4 percent is found; otherwise, the remainder of the current arc is abandoned and the next one is sampled. Stream segments listed in the output file are then split at the specified UTM coordinates using an automated editing procedure. After the editing procedure, the updated slope and elevation values were written to the edited hydrography coverage.

Stream Buffer Vegetation Tabulation

A 30-metre raster stream buffer was generated along both sides of single-arc streams in the hydrographic data layer. The actual cell size implemented to model stream buffers was 6 metres; thus, the width of each buffer was modeled with five 6-meter cells. Each raster buffer was indexed to the vector hydrography line coverage, and the percentage of each land-cover category (Table 2) was written to its respective

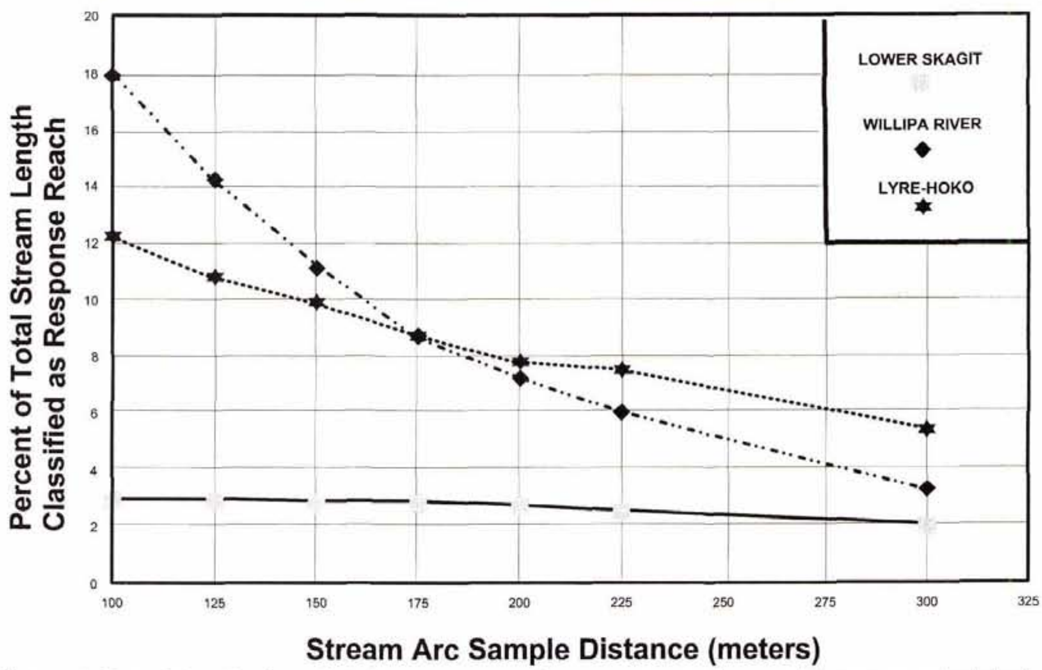

Figure 1. Plot of length of predicted response reaches versus sample arc distance as calculated for the Lower Skagit, Willapa River, and Lyre-Hoko WRIAs.

arc in the arc attribute table. Raster procedures were incorporated to speed up the buffer processing time through the use of rapid cross-tabulation procedures between the buffer areas and the raster vegetation layer. For wider streams and rivers which are depicted with double arcs, buffers were extended from each bank and vector processing procedures were used to summarize vegetation within each stream buffer. Statistics were then generated from the buffer summary tables for each arc.

Summary Reports

WRIA summary reports were organized by WAU and listed attributes for streams, vegetation, roads, and slope (Table 3). Map and bar chart plot files produced from WRIA coverages and summary table attributes were used to plot graphical aids for watershed assessment teams. WRIA maps can be generated on a large format plotter to depict the following themes: (a) response, transport, and source channel types; (b) vegetation classes; (c) transportation networks; (d) slopes; and (e) WRIA and WAU boundaries.

Validation of Stream Channel Type Predictions

Validation was performed by comparing field observations with GIS-generated channel type predictions. Field assessment data were provided to the project for the nine Lower and Upper Skagit River WAUs previously listed. The length of the sample reaches generally ranged from 100 to 300 metres, and the midpoint of each reach was delineated on a topographic map. The comparison is accomplished through creation of an error matrix for each WAU (Story and Congalton, 1986). A Kappa coefficient was calculated using discrete multivariate statistical techniques as a measure of the overall agreement between the stream channel type predictions and field observations (indicated as the major diagonal) versus agreement that is contributed by chance (Congalton *et al.*, 1983). The Kappa coefficient was calculated based on the formula given by Hudson and Ramm (1987).

Results

Of the 164,083 km of stream reaches analyzed, 23.2 percent (38,002 km) were categorized as response reaches (≤4.0 percent slope), of which 8.7 percent (3,302 km) were associated with late-seral and 20.7 percent (7,867 km) with mid-seral stage forest stream vegetation.

Hydrographic Data Scale

Plate 1 clearly illustrates the deficiencies of the 1:100,000-scale hydrography stream network (compared to the 1:24,000-scale product) for depicting the actual stream channel network. In the Finney Creek WAU, a total of 490.1 km of stream length are contained in the 1:24,000-scale hydrography compared to 94.8 km in the 1:100,000-scale product. More importantly, the results of the response reach analyses indicate a significant underestimate of response reaches associated with 1:100,000-scale coverage compared to the 1:24,000-scale coverage (43.0 km and 64.9 km, respectively). The smaller scale EPA hydrographic data, in addition to lacking resolution in the number of streams, was also deficient in absolute stream orientation detail.

Stream Slope Sampling

Results of the stream slope sampling procedure are presented in Figure 1. The optimal sample length corresponds to the

TABLE 3. WRIA SUMMARY REPORT ATTRIBUTES, EXTENT, AND DESCRIPTION.

Attribute	Extent	Description
Streams	WRIA/WAU	Total kilometres and stream density. Stream density and percent by predicted channel reach type.
Seral Stage	WRIA/WAU/ Stream Buffer	Hectares and percents.
Slope	WRIA/WAU	Hectares and percent of landscape slope in three classes.
Roads	WRIA/WAU	Total kilometres and road density.

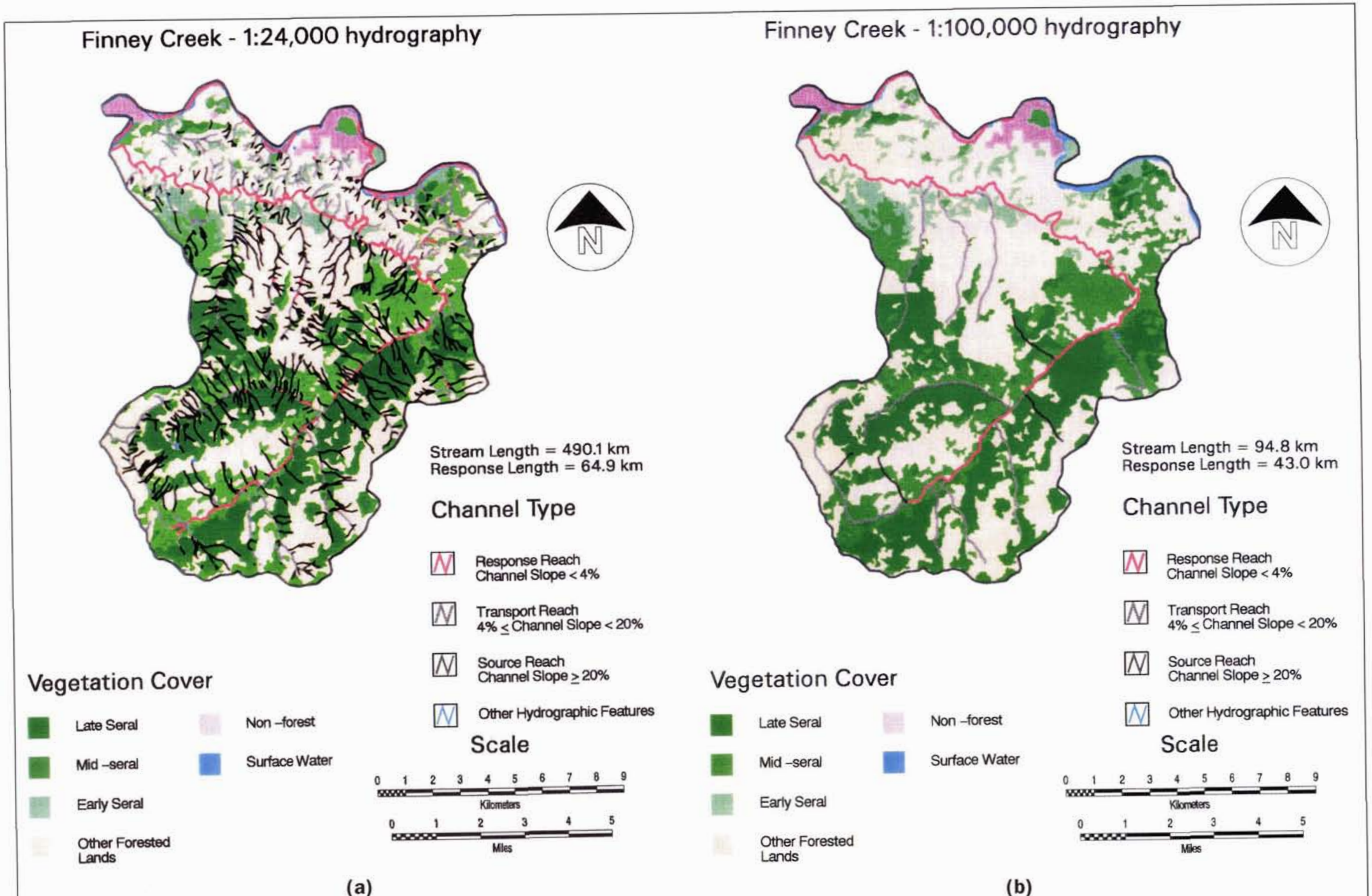

Plate 1. Comparison of (a) 1:24,000-scale and (b) 1:100,000-scale hydrography data. Note the greater stream density and 50 percent increase in response reach length associated with the 1:24,000-scale data.

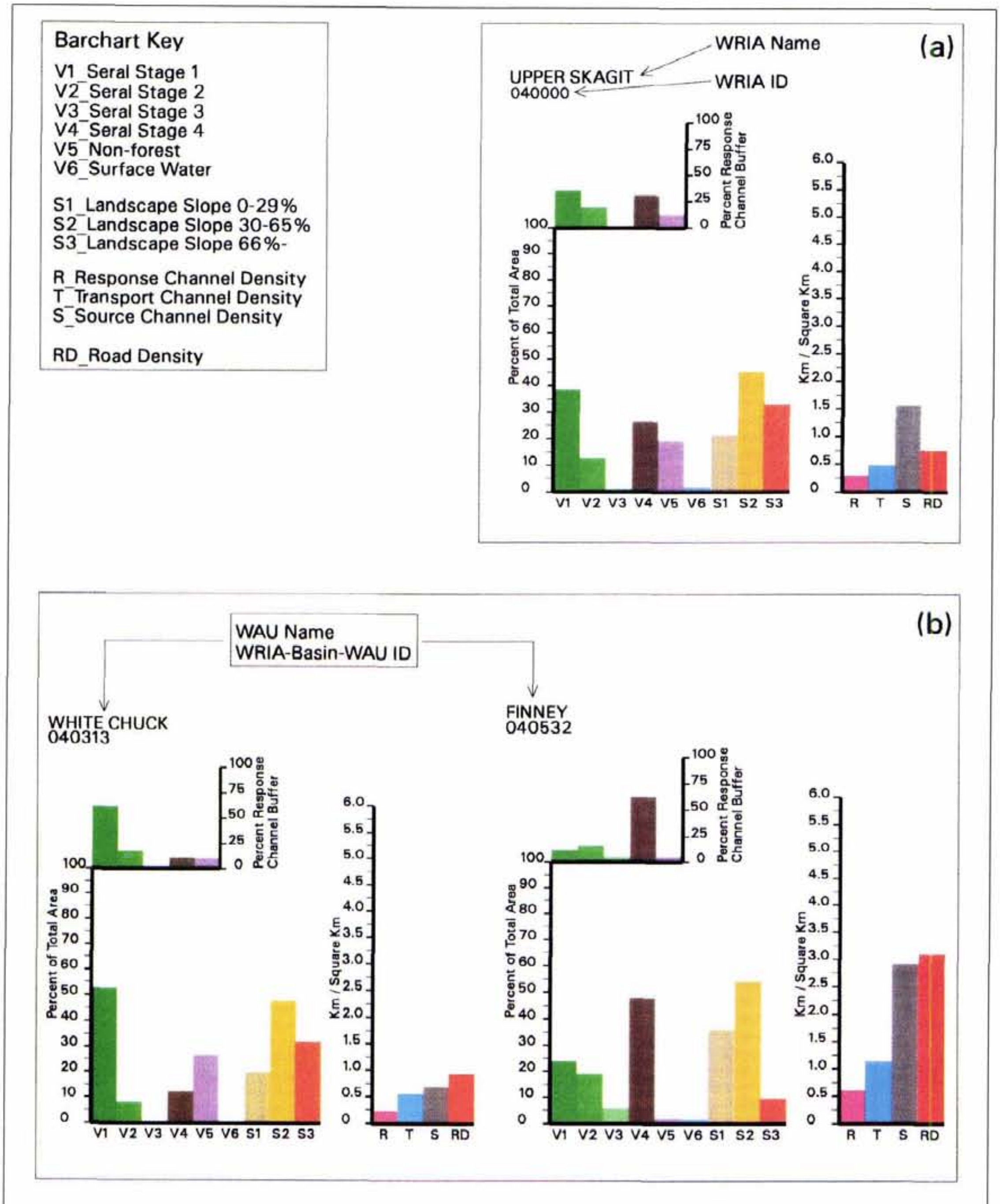

Plate 2. Example WRIA bar chart (a) data presentation and WAU bar charts (b) standard outputs produced for all of western Washington State.

maximum stream-arc sampling distance that provides the maximum response reach length. Seven sample distances (100, 125, 150, 175, 200, 225, and 300 metres) were evaluated for each of three WRIAs (Figure 1) which represented a broad range of physiographic conditions present throughout western Washington State (Lower Skagit, Willapa River, and Lyre-Hoko). The objective was to determine the maximum effective distance to minimize computational requirements, where 100 metres is the minimum feasible sampling length. Sample length must be sufficiently long to capture the inherent variation of the DEM. Short sample distances are ineffective because the elevation change over the sample length is often very low or zero, and exceedingly long sample lengths tend to mask slope changes.

The stream slope sampling procedure enhanced the detection of response reaches located between stream confluences and the base of steep mountain slopes, and it identified additional response reaches within relatively long stream lengths in moderate terrain. Evaluation of the sample distances indicate that a distance of 100 metres, the shortest distance tested, generated the greatest response length for all WRIAs. As shown for the Willapa WAU (Figure 1), the total length of predicted response reaches tends to decrease rapidly as sample length increases from 100 metres to 175 me-

Table 4. Correspondence between Response Reach Land-Cover Categories versus Stream Bed Morphology.

Response Reach Land-Cover Categories[a]	Percent Reaches Classified as Forced Pool-Riffle
Late-Seral Stage	100% (n = 8)
Mid-Seral Stage	78% (n = 18)
Early-Seral Stage Other Forest	74% (n = 68)
Non-Forest	35% (n = 26)

[a]Observations made along 30-m buffer each bank.

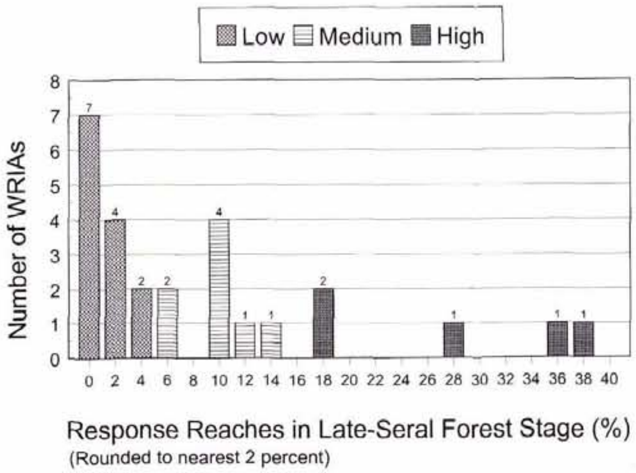

Figure 2. Frequency distribution of percent WRIA response reaches in late seral forest stages for western Washington State.

tres, then declines more gradually to 300 metres. The Lyre-Hoko's decline was more gradual than the Willipa, whereas the Lower Skagit was only slightly sensitive to sampling distance. Variations in sampling distance appear to have the greatest effect in locations with moderate to steep terrain. For example, 81 percent of the landscape of the Lower Skagit WRIA had a slope less than 30 percent; the percentage of area within the Willipa and Lyre-Hoka WRIAs with a landscape slope less than 30 percent was 75 and 57 percent, respectively. It appears that hydrologic units with moderate to steep terrain experience the greatest relative increase in response length with decreased sampling distance. Although a 100-metre sample distance maximizes the length of response reaches, a sample distance of 150 metres was applied to minimize errors of commission, and simultaneously reduce processing time and data volume.

Stream Bed Morphology

Field observation data were collected from a total of 120 response reach stream segments in both the Lower and Upper Skagit WRIAs in order to examine the association between stream buffer zone vegetative land cover and stream bed morphology (Table 4). Results indicate that late-seral stage forests are associated with forced pool-riffle stream bed morphology. However, the small number of samples (n = 8) precludes the drawing of any final conclusions. Response reach buffer zones containing any type of forested land cover had a 77 percent correspondence to forced pool-riffle stream bed morphology. Non-forested buffer zones were associated with forced pool-riffle morphologies in 35 percent of the field observations.

Habitat Evaluation

Results applicable to the evaluation of salmon habitat in western Washington State are illustrated in Plate 2. The summary bar chart generated for each WRIA and WAU provides a means of comparing potential salmon habitat conditions across WRIAs and to support intra-WRIA assessments. The summary table data for an entire WRIA and individual WAUs include the following information categories: (a) vegetation percent by class; (b) vegetation percent by class within response channel buffers; (c) response, transport, and source channel density; (d) road density; and (e) landscape slope. Summary graphics include drainage density by channel type and forest seral stage coverage expressed as a percent of total watershed and percent area within buffers around response reaches. These data can facilitate the rapid inference of general stream-side conditions and potential for LWD recruitment. In addition, road density and slope data provide some insight to the potential for sedimentation impacts within a given hydrologic unit.

In western Washington more than one fourth of WRIAs have no late-seral stage forest bordering response reaches, and 73 percent of WRIAs have late-seral stage forests along 10 percent or less of the total response reach length (Figures 2 and 3). These areas tend to be associated with urban, agricultural, or commercial forest land use. Only three WRIAs have more than 20 percent of their response reach length bordered by late-seral stage forests, and these lie partially within national parks or wilderness areas. Overall, only 8.7 percent of response reaches flow through late-seral stage forests. This

Figure 3. Identification and location of the highest quality WRIAS in western Washington State. Note that WRIAS 2 and 6 were not processed because they contain only islands.

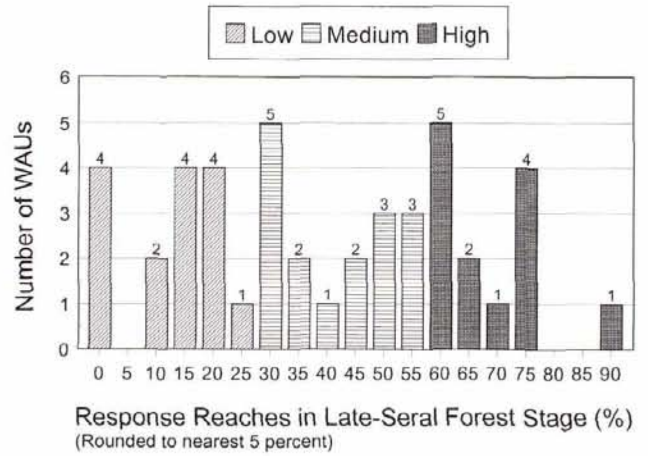

Figure 4. Frequency distribution of percent Upper Skagit WAU response reaches in late-seral forest stage.

provides the first quantitative regional characterization of the extent of habitat modifications that accompanied urbanization, agricultural development, and industrial forestry.

Within the Upper Skagit River basin, approximately one tenth of WAUs have late-seral stage forests bordering 10 percent or less of the total response reach length (Figures 4 and 5). However, 43 percent of WAUs have late-seral stage forests along 50 percent or greater of the total response reach length. Of the 20 WAUs identified with late-seral stage forests along 25 percent or greater of total response reach length (highest quality WAUs), eight (40 percent) are above major dams (Figure 5). As in the province scale assessment, land use in the WAUs with low percent late-seral stage tend to be dominated by agricultural and urban development, although some of these WAUs are predominantly industrial forests. WAUs with high percent late-seral stage tend to be largely within the boundaries of national parks, national recreation areas, or wilderness areas.

Accuracy Assessment

Although validation was limited to nine WAUs, the basic relationships between physical processes and stream habitat are thought to be consistent across the study area, and the validation for those nine watersheds should be representative for western Washington State. The results of the validation are presented in an error matrix (Table 5). The identification of response reaches was 96 percent accurate, and the overall accuracy of all channel type predictions was 79 percent, Kappa statistic = 0.64 (n = 158). Errors of omission and commission associated with predicted response reaches were 24.0 and 4.0 percent, respectively. As mentioned above, the use of the 150-metre arc sampling distance tended to minimize commission errors while increasing errors of omission between response and transport channel types. In theory, these omission errors could be reduced by using a 100-metre arc sampling distance, but commission errors would likely increase. However, the ultimate limiting factor is the resolution and quality of the DEM data.

Discussion

The intent of this effort was to produce a regionally consistent information base that federal agencies could use for planning or prioritizing salmonid habitat restoration opportunities in the PNW. Our analyses were based on simple concepts that are consistent with our understanding of habitat-forming processes in western Washington State. These are as follows: (a) channel slope largely determines the range of potential channel morphologies; (b) large woody debris abundance modifies within channel type morphology; and (c) salmonid habitat utilization increases with increased LWD abundance in the response reach channel type. We also pre-

Figure 5. Identification and location of the highest quality WAUs in the Upper Skagit WRIA.

TABLE 5. ERROR MATRIX COMPARING GROUND VISITED REFERENCE DATA TO THE PREDICTED STREAM REACH DATA.

		Ground Visited Reference Data					
		Response	Transport	Source	Row Total	% Correct	% Commission
Predicted Channel Types	Response	74	3	0	77	96	4
	Transport	23	36	4	63	57	43
	Source	0	3	15	18	83	17
	Column total	97	42	19	n = 158	Overall Accuracy 125/158 = 79%	$\hat{K}$ = 0.64
	% Omission	24	14	21			

sumed that large conifer riparian forests tend to be associated with greater LWD abundance than are open or early-seral stage riparian areas. Hence, the fundamentally important outputs of our analyses are the extent and location of response reaches (slope <0.04) and the condition of riparian forests along response reaches. The extent and location of response reaches identifies areas that may provide suitable habitat for salmonids, and riparian forest conditions indicate the likelihood that those reaches have the forced pool-riffle morphology that salmonids favor.

Our accuracy assessment generally supports the assumptions listed above. However, users of such data should be aware that, while the model typically under-represents the extent of response reaches, areas identified as response reaches are likely to be correct. Field efforts designed to more accurately identify locations of potential salmonid habitat should therefore focus on areas identified as transport reaches. Field data suggest that those response reaches incorrectly identified as transport reaches are often located where tributary channels enter the valleys of larger channels.

The analyses were less accurate at predicting channel morphology within response reaches, although results generally support the hypothesis that increased forest age is associated with increased LWD abundance. Also, we found little difference in the proportion of forced pool-riffle channels between early and mid forest seral stages. Histograms of GIS-generated data provide a broad-brush description of channel and riparian conditions at scales that are useful to managers with statewide or regional jurisdiction (Figure 2). These data provide a crude but comprehensive characterization of landscape and stream channel attributes that influence the abundance and condition of salmonid habitats.

A qualitative comparison between the preceding results and a field-based assessment of habitat losses in the Skagit River basin reveals that our GIS-based predictions are generally consistent with field data collected independently of this study. Based on the results of our analysis, we predict that the greatest habitat losses have occurred in the Skagit river floodplain and delta where little late-seral stage forest remains. Beechie *et al.* (1994) found that by far the greatest proportion (73 percent) of coho salmon rearing habitat losses were associated with diking, ditching, and dredging in the floodplain, and that these losses were associated primarily with urban and agricultural land uses. Hence, our GIS-based results at least grossly predict the same result as a field-based assessment.

Beechie *et al.* (1994) further noted that industrial forestry had less impact on coho rearing habitat losses at the river basin scale, but was nevertheless strongly associated with habitat losses in tributary streams (channel widths less than 10 metres). Thus, forestry was associated with less severe impacts to coho salmon rearing habitat than were urban and agricultural uses. Our results are also consistent with this relative ranking of severity of impact by type of land use. We show no late-seral stage forest in WAUs where non-forest land uses dominated response reach zones, suggesting that the most severe impacts to habitat would be located in those WAUs. By contrast, we found a broader range of percent late seral stage in WAUs where forestry borders the majority of response reaches, indicating that impacts to rearing habitat should be less severe in those WAUs.

Although not all response reaches were bordered by late-seral stage forest prior to European settlement, our results suggest a dramatic change in riparian conditions during the last 100 to 200 years. Prior to European settelement, forest fires, floods, and channel migration were dominant influences on stand ages and types near streams (e.g., Agee 1988). Certainly, these processes would create a patchwork of stands along channel networks, resulting in a range of forest types and seral stages along response reaches. Our data for WAUs contained partially or fully within national parks and wilderness areas give some indication of this patchwork (Figure 6). The median percentage of response reaches in late-seral stage WAUs located substantially in park and wilderness areas was 54 percent. This compares to 22 percent for commercial forestry and less than 10 percent for urban-agriculture land uses. We caution, however, that the percentages shown in Figure 6a should not be construed as representative of "natural" conditions because many WAUs contain significant amounts of development.

In addition to a relative ranking, the data distributions can provide useful information for the development of preservation and/or restoration prescriptions. For example, some WRIAs have a relatively low percentage of response reaches in the late-seral forests, but a high percentage in mid-seral forests. A rational restoration consideration for these WRIAs may be the preservation of existing mid-seral forests in WAUs with a high density of response reaches. However, use of these analytical tools for identifying tasks or priorities for salmon habitat preservation and restoration can only be accomplished through a process that includes involvement of experts with knowledge of *in situ* habitat conditions. With the proper expertise and selected ancillary data (e.g., physical barriers to fish migration), map products identifying specific attributes of WRIAs and WAUs could provide a valuable

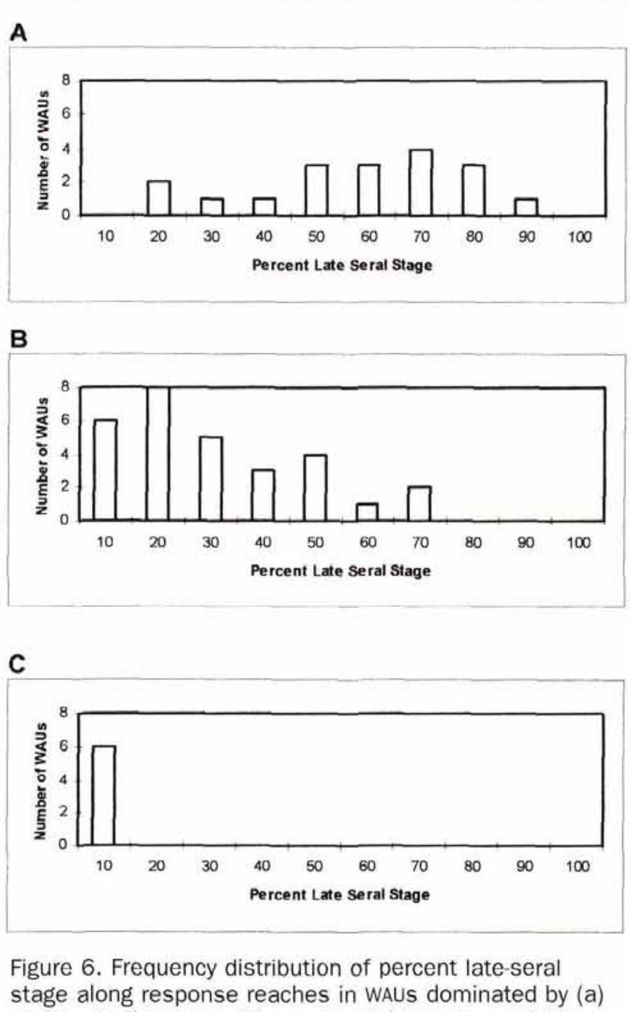

Figure 6. Frequency distribution of percent late-seral stage along response reaches in WAUs dominated by (a) park and wilderness, (b) commercial forestry, and (c) urban-agriculture land uses.

data source to help prioritize the expenditure of preservation and restoration resources.

Conclusions

Our efforts demonstrate that remote sensing data and GIS methods can be applied to assess landscape attributes that influence the condition of salmon habitat at sub-basin to watershed scales. GIS-based analytical products can be used to predict the locations of response reaches likely to provide salmon habitat. By using GIS buffering procedures along response reaches, the likelihood of finding a forced pool-riffle morphology based on the adjacent stream bank vegetation associations can be estimated. Both types of predictions have quantifiable error rates. These products could be used to target reaches where predictions are poor (e.g., the 23 percent of reaches predicted to be transport reaches that were response reaches), thereby increasing the efficiency of field efforts. Furthermore, such products can rapidly identify the quantity, extent, and condition of habitats at a scale useful for prioritizing regional protection or restoration efforts. We believe that such a wide-area, uniform database (uniform map themes and uniform coordinate system) can complement existing watershed screening protocols and help accomplish prioritization more rapidly and with greater reliability and objectivity.

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