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U.S. DEPARTMENT OF COMMERCE
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National Marine Fisheries Service
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1 Introduction

Numerous Evolutionarily Significant Units (ESUs) of salmon and steelhead in California and the Pacific Northwest have been listed under the U.S. Endangered Species Act (ESA). In response, NOAA Fisheries convened Technical Recovery Teams (TRTs) to develop biological viability criteria for the listed ESUs. An understanding of biological structure is a critical first step to assessing population viability and potential persistence of ESUs (Meffe and Vrijenhoek, 1988; McElhany et al., 2000). TRTs evaluate population structure within each ESU under historical conditions, because this structure resulted from ecological and evolutionary dynamics that played out across the landscape before recent anthropogenic disruption. The historical population structure therefore represents a state for which we are most certain that the ESU persisted over long periods and is a "baseline" for evaluating the status of an ESU under current or projected conditions. Because populations that were important to ESU persistence in the past are likely to be important to ESU persistence in the future, understanding the historical template is critical to reducing uncertainty in assessments of current or future viability scenarios.

Unfortunately, historical data on population abundance and distribution are sparse and of limited spatial extent or resolution. Furthermore, information on current conditions is often insufficient or are too influenced by anthropogenic disruption of natural processes to support inference regarding historical structure within a given ESU. TRTs for coastal California and Oregon[1] have therefore adopted a GIS-based modeling approach to predict historical population structure as a function of the geomorphic and hydrologic processes that generate suitable freshwater habitat for critical life-history stages of each species. This approach to broad-scale classification of areas according to their "intrinsic potential" (IP) to exhibit suitable habitat was originally developed for coho salmon and steelhead watersheds draining the Coast Range of Oregon (Burnett et al., 2003), and is supporting analysis of historical population structure for the Oregon Coast Coho Salmon ESU and the three ESUs in the NCCC Recovery Domain (Lawson et al., in prep.;

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[1]Two TRTs are charged with developing biological viability criteria for five listed ESUs of salmon and steelhead that occupy watersheds tributary to the Pacific Ocean between the Columbia River (exclusive), and northern Monterey Bay, California. The TRT for the Oregon/Northern California Coast (ONCC) Recovery Domain is charged with analyses for the Oregon Coast coho salmon (OC-coho) and Southern Oregon/Northern California Coast coho salmon (SONCC-Coho) ESUs. The TRT for the North-Central California Coast (NCCC) Recovery Domain is charged with analyses for the Central California Coast coho salmon (CCC-Coho), North-Central California Coast steelhead (NCCC-Steelhead), Central California Coast steelhead (CCC-Steelhead) ESU, and California Coastal Chinook salmon (CC-Chinook) ESUs.

Bjorkstedt et al., in prep.).

In this report, we describe implementation of this approach to coastal watersheds between Cape Blanco, Oregon, and Monterey Bay, California and characterize GIS data sets developed for listed ESUs of salmon and steelhead in this region. Specifically, we adapt the approach developed by Burnett et al. (2003) to predict IP for rearing habitat of coho salmon (*Oncorhynchus kisutch*), winter steelhead (*O. mykiss*) and fall-run Chinook salmon (*O. tshawytscha*). Note that we do not assess intrinsic potential for summer steelhead and spring-run Chinook salmon because these life-history strategies have very specific habitat requirements (e.g., deep, cold pools in which the adults spend the summer) that are not readily identified from available GIS data. In addition to the technical description of the model and analysis, we also offer guidance regarding appropriate interpretation and use of these results in recovery planning for listed salmonids.

2 Intrinsic potential: concept and general model

The concept of a stream's "intrinsic potential" to exhibit suitable habitat for a particular species or life stage emanates from a hierarchical perspective of fish-habitat relationships (sensu Frissell et al., 1986; Montgomery and Buffington, 1998). In this view, landform, lithology, and hydrology interact to govern movement and deposition of sediment, large wood, and other structural elements along a river network. These broader-scale characteristics and processes thereby control gross channel morphology at the scale of stream segments or reaches, as reflected in the frequency and characteristics of constituent habitat units (e.g., pools, runs, riffles, side-channels, etc.). The IP concept assumes that this hierarchy of organization, structure, and dynamics of physical habitat is reflected in the biological organization of stream communities. In the case of salmonids, the biological response manifests itself as heterogeneity in the distribution, abundance, and productivity of different species and life stages within a stream network. The underlying framework for the IP models assumes that three primary indicators of landform and hydrology — channel gradient, an index of valley width, and mean annual discharge — reasonably constrain channel morphology and hence the potential of a reach to express habitat conditions favorable to a particular salmonid species at some stage of its life. These three characteristics are effectively constant features of the landscape, and thus provide the basis for predicting both potential habitat under historical conditions and the potential for physical processes to recreate suitable habitat if left to operate more or less naturally. Among-species or life-stage differences in habitat affinities are accommodated through species-specific curves relating suitability to the three physical metrics.

Burnett et al. (2003) describe a practical model that translates stream reach characteristics into a measure of intrinsic potential in two steps. First, reach-specific values for each characteristic (i.e., gradient, valley constraint, and mean annual discharge) are converted to habitat suitability scores through functions ("suitability curves") that convert the value of each variable to a scale of 0-1. Suitability curves are specific to species and life-history stage (see §3.3 below). Second, reach-specific IP is calculated as the geometric mean of reach-specific suitability scores for each of the three characteristics[2]. Combining the marginal effects of each reach characteristic in this way is directly analogous to the theoretical basis of a limiting factors analysis: a low value based on a single characteristics will dramatically reduce or zero-out IP for a stream reach, and in these instances, other reach characteristics are uninformative with respect to habitat potential.

3 Implementation south of Cape Blanco

In the following sections, we provide a brief overview of the basic approach outlined in (Burnett et al., 2003), but focus in more detail on specific nuances of our implementation of the IP model for watersheds south of Cape Blanco.

3.1 Generating stream networks and reach attributes

Calculating IP is a multi-step process that occurs both outside and inside a GIS. The first step creates a stream network from the Digital Elevation Model (DEM) and precipitation data that defines individual reaches and calculates values of gradient, valley floor width, and discharge for each. The second step creates suitability curves for these three variables based on life-history and habitat association of each species and life-stage. Finally, to marry these two steps, Burnett et al. (2003) wrote a series of species-specific processing scripts (Arc Macro Language, Environmental Systems Research Institute, Inc.[3,4]) to

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[2]Mathematically, for stream reach k, $\mathrm{IP}_k = \sqrt[3]{f_D(D_k) \cdot f_G(G_k) \cdot f_V(V_k)}$, where D_k, G_k, and V_k are mean annual discharge, gradient, and valley constraint, respectively, of reach k, and each f_x maps the appropriate characteristic x onto a scale of 0-1.

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calculate the IP score for each reach.

To construct a stream network, we implemented a model developed by Miller (2003) that synthesizes grid-based data on topography derived from a 10 m resolution DEM[5] and mean annual precipitation derived from the PRISM model (Daly et al., 1994)[6]. To run the model (Miller, 2003) (which is implemented outside of a GIS in a series of Fortran programs), we generated binary files of regional-scale elevation and precipitation grids. Beginning with these grids, we clipped the DEM and precipitation files to the watershed boundaries. The last input needed is a parameters file, and the only substantial change to the default inputs was to include regionally-specific equations relating precipitation to discharge (See §3.2 for specifics). The model was run on a watershed by watershed basis. Watersheds were defined *a priori* based on 1:100K hydrography (USGS 2003), sixth-field hydrologic unit code (HUC) boundaries (Fire and Resource Assessment Program (FRAP), 1999; National Resources Conservation Service (NRCS), 2002), and where required, manual delineation informed by topography. For very large basins (e.g., the Rogue, Klamath, and Eel rivers), it was necessary to model major tributaries and sections of mainstem river separately, and subsequently to reassemble the basin in GIS[7]. For each watershed, the model creates several output layers, including: Flow Direction of the raster streams within the watershed using the Tarboton Method (Tarboton, 1997), Flow Accumulation of the streams, and a vector version of the DEM derived streams (whereby each reach includes information on the three variables that are the basis for IP: gradient, valley constraint, and mean annual discharge).

In the course of constructing the stream network, the model dynamically defines reaches on the order of 50-200 meters long, basing reach breaks on changes in gradient. In the resulting stream network, each reach is characterized by its gradient (averaged over

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[5]10 m DEM coverage was not available for our entire study region at the time of analysis. Therefore, where seamless, original 10 m DEM coverage was not available, we generated a 10 m DEM by applying a spline to interpolate a seamless 30 m resolution DEM to 10 m resolution. Comparisons of derived properties (e.g., stream gradient) aggregated at watershed scales, and the general structure of resulting watersheds show negligible differences between analyses based on interpolated 10 m DEMs and analyses based on independently derived 10 m DEMs.

[6]The PRISM data set is derived by interpolating climatic observations from the period 1961-1990 at a spatial resolution of 2km by 2km. The interpolation scheme accounts for the influence of elevation, aspect, and proximity to the coast on climatic variables such as temperature and precipitation (Daly et al., 1994).

[7]The model (Miller, 2003) includes a Fortran routine to "stitch" the sub-watersheds back together. This routine matches stream topology during reassembly, and transfers discharge values from the stream at the outlet of the upstream watershed to the first reach in the downstream watershed.

the entire reach), valley width[8], and mean annual discharge (calculated at the downstream end of the reach).

Post processing on each of the three variables generated by the model also occurs within the GIS; specifically, gradient is calibrated based on field measurements, discharge is converted to metric units, and valley-floor width is used to generate the index of valley constraint (Burnett et al., 2003)[9]

3.2   Accounting for latitudinal gradients in climate

By implementing the IP model directly, we assumed that geomorphic structure and precipitation interact similarly to generate stream networks in northern California and in coastal Oregon, for which the IP model was originally developed. We attempted to evaluate this assumption by estimating regional models for mean annual discharge as a function of catchment area and mean annual precipitation. To accomplish this, we assembled discharge data for stream gages with at least 20 years of data during the period for which the PRISM precipitation data were developed and with little or no evidence of substantial upstream diversion, extraction or elevated evaporative loss[10].

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[8]Miller (2003) explains that valley floor width is "estimated as the length of a transect that intersects the valley walls at a specified height above the channel. Since the orientation of the valley is unknown, transect orientations is varied to find that which provides the minimum length. The height above the channel is specified as 2.5 times estimated bank-full depth, given as a function of drainage area. The value is currently coded in as $H_{bf} = 0.36A^{0.2}$, where H_{bf} is bank-full depth and A is drainage area in square kilometers (based on data in Benda (1994)). Thus the height above the channel from which the transect is extended varies from a little less than a meter for small streams to a little over three meters for large streams."

[9]Burnett et al. (2003) derived an index of valley constraint by dividing valley floor width by active channel width, the latter of which was calculated as follows, $ACW = 2.19108 + 1.32366 * \sqrt{D}$, where D is mean annual discharge (in ft^3/s). N.B. this V_k differs from the V_k enumerated in Oregon Department of Fish and Wildlife sampling protocol (http://gisweb.co.tillamook.or.us/library/standards/StreamHabitatMethods.pdf), in that this V_k is derived from a DEM as opposed to field based measurements. Because of this, our breaks in "constrained" and "unconstrained" are not arithmetically equivalent to ODFW's, though they describe the same phenomenon. Note that the stream network and its attributes are the basis for all subsequent calculations, regardless of species or life-history stage.

[10]Gages were excluded on the basis of evidence of direct diversion extracted from Agajanian et al. (2002), Christy (2003), or USGS (2003). Estimates of extractions for irrigation were compiled from estimates of irrigated area and HUC-level irrigation rates using information in Solley et al. (1998) and Vogelman et al. (2000). Actual or estimated evaporation rates were used to evaluate losses from non-diversion reservoirs. If estimated evaporation rates or diversions for irrigation or water supply from the watershed above a particular gage exceeded 2% of mean annual discharge, that gage was excluded from

Preliminary analyses indicated that the relation of mean annual discharge to catchment area and mean annual precipitation in the SONCC Recovery Domain was essentially identical to that for coastal Oregon. The final discharge-precipitation relationship we developed for coastal watersheds throughout the study area was also very similar to that used for coastal watersheds north of Cape Blanco[11]. On the basis of substantial climatic differences, we estimated a separate model to predict discharge in watersheds in the San Francisco Bay[12].

3.3 Suitability curves

Suitability scores express the "likelihood" that suitable habitat will occur in a reach with a particular value for a characteristic, independent of the value of the other characteristics. In general, the form of the relationship between reach characteristics and habitat suitability is not known precisely. What often is reasonably well known is the range of values for a given characteristic that almost always yield favorable habitat as well as the range of values for which favorable habitat almost never occurs. Given the uncertainty associated with intermediate values, a simple linear relation is generally assumed to fill in the gap between values corresponding to "good" and "poor" habitat potential. Note that regardless of life-history stage, the upper extent of tiny positive values for gradient reflects the ability of adults to ascend reaches of varying steepness, and thus defines the range of accessible habitat.

Suitability curves are defined for each reach characteristic and for a species and life-history stage. These functions are used to convert reach-specific values for each of the three attributes to a scale of 0-1, and the resulting scores represent the effects of each physical attribute on the potential of a stream reach to exhibit high quality habitat. Our ability to measure "habitat quality" directly is extremely limited, and available data sets, while informative, are generally insufficient to support extensive, rigorous statistical estimation of the functional relationship between all three stream characteristics and

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further analyses.

[11]The final model for the region spanning coastal watersheds from Cape Blanco to Santa Cruz predicted mean annual discharge, D (in $m^3 s^{-1}$) according to $\ln(D) = -11.445 + 1.003 \ln(A) + 1.467 \ln(P)$ (n = 29, $r^2 = 0.988$), where A is (planar) catchment area in ha and P is mean annual precipitation in mm. For comparison, the relation for coastal Oregon is $\ln(D) = -11.972 + 0.99 \ln(A) + 1.593 \ln(P)$, which was taken directly from the Miller 2003 model. Note that these models are of the same form as those developed by the Oregon Department of Forestry (Lorensen et al., 1994).

[12]Based on data for San Francisco Bay and watersheds in the western Central Valley, we estimated $\ln(D) = -13.047 + 0.876 \ln(A) + 2.171 \ln(P)$ (n = 20, $r^2 = 0.968$).

their marginal effects on habitat quality. Suitability curves, therefore, represent expert synthesis of data on fish distributions and abundance in the context of general habitat requirements of a particular life-history stage of a particular species. Typically, such syntheses are based on density estimates (e.g., the number of juvenile coho salmon per 100 m of stream), which are assumed to provide a measure of the amount of high quality habitat in a reach, across a range of habitat characteristics. The assumption that habitat suitability is proportional to use (i.e. density) in unmanaged systems extends well beyond the studies where these models originated (the Umpqua Land Exchange Project (ULEP) and Coastal Landscape Analysis and Modeling Study (CLAMS)), and is a basis for much of ecology.

Figure 1 illustrates the suitability curves used to calculate IP for the relevant life history stages of each of the three species addressed in this report. These curves are based on those from CLAMS. Somewhat similarly, "index values" were developed in the ULEP[13]. Table 1 provides some of the historical references used in the development of the suitability curves, and additional data sets that we consulted when evaluating whether relationships between stream characteristics and fish distributions provided evidence that different suitability curves were required for our study region. With the exception of Engle (2002), none of these data suggested that altering the curves for application to California was warranted. Based on Engle's (2002) work, we extended the range of gradients that were accessible to adult steelhead and consistent with high likelihood of suitable habitat for juvenile steelhead (Figure 1). We also reduced slightly the suitability of highly constrained reaches for juvenile steelhead to recognize that these fish use (and perform well in) habitats such as pools that are less common in highly constrained reaches.

3.3.1 Life history context for suitability curves

Understanding the ecology and habitat requirements of a given species at its various life history stages is useful for interpreting and understanding the distribution of IP scores within a basin. We therefore provide below a brief description for the relevant life history stage for each of the species addressed in this report.

Juvenile coho salmon   Juvenile coho salmon spend at least one summer and one winter in freshwater, although some individuals may spend an additional year in freshwater.

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[13]CLAMS and ULEP differed in that CLAMS used a geometric mean to calculate IP whereas ULEP use an arithmetic mean. ULEP used discrete classes for the three attributes rather than suitability curves. ULEP also did not attempt to interpret IP and actual habitat conditions separately. Lastly, CLAMS and ULEP interpret constraint for steelhead differently.

These fish exhibit traits, such as relatively large fins and laterally compressed bodies, that are believed to be adaptations to living in the slower-velocity habitats where they most commonly occur. During the summer, juvenile coho salmon generally prefer pool habitats over runs and riffles (Bisson et al., 1988). Juvenile coho salmon often move out of the main channel and seek refuge in side channels, alcoves, and other off-channel habitats during periods of high stream discharge (Tschaplinski and Hartman, 1983; Meehan and Bjornn, 1991; Bell et al., 2001). Together, these attributes and behaviors likely explain why juveniles are most abundant in low-gradient (usually <2%-3% but occasionally up to 5%), unconstrained reaches as opposed to constrained reaches or steeper headwater streams.

The suitability curves that form the basis of IP predictions for juvenile coho salmon reflect the likelihood that stream reaches will exhibit substantial pool and off-channel habitat as a function of their geomorphological and hydrological characteristics (Figure 1a-c). These suitability curves are identical to those used by Lawson et al. (in prep.) to predict IP for watersheds in coastal Oregon.

Juvenile (winter) steelhead The juvenile phase spans at least one summer and one winter in freshwater, but is more variable and of greater maximum duration than is observed for coho salmon. Following emergence in spring, steelhead fry typically adopt feeding stations in shallower portions of riffles or pools, moving into progressively faster and deeper water as they grow (Bisson et al., 1988). Juvenile steelhead exhibit a stream-lined body morphology that is thought to be an adaptation for life in faster water currents (Bisson et al., 1988). Although steelhead tend to prefer and grow faster in pool habitats, as young-of-the-year, they are commonly displaced to riffle habitats through competitive interactions with larger, more aggressive coho salmon when the latter are abundant (Bugert and Bjornn, 1991; Young, 2004). Such displacement is not observed for older, larger juvenile steelhead. The spawning distribution of steelhead overlaps with that of coho salmon; however, because steelhead tend to prefer higher gradients (generally 2-7%, though they may be found in reaches with gradients up to 12% or more), their distribution tends to extend farther upstream. In some watersheds, steelhead will even spawn in ephemeral streams, with juveniles migrating downstream to permanent waters to rear.

The suitability curves that form the basis of IP predictions for juvenile steelhead reflect the likelihood that stream reaches will exhibit substantial higher-energy habitats as a function of their geomorphological and hydrological characteristics (Figure 1d-f). To some degree, these curves implicitly include the consequences of ecological interactions with coho salmon; however, these interactions take place at local scales, and in most if not

all cases where juvenile coho salmon occur, they are sympatric with juvenile steelhead at the reach scale. Note that although we found no support for implementing a temperature-based constraint on the predicted distribution of steelhead in our study area[14], juvenile steelhead are not likely to experience substantial "competitive release" with respect to the distribution of high quality habitat in areas where coho salmon are excluded by temperature. Instead, because the metabolic demands of juvenile steelhead increase with temperature, it is likely that juvenile steelhead will continue to favor higher velocity habitats that provide a greater rate of drift to supply their increased foraging needs (Smith and Li, 1983).

Juvenile Fall-run Chinook salmon   Fall-run Chinook salmon occur in rain-dominated systems or the lower portions of systems with both rain and snowmelt influence, and tend to spawn in low-gradient reaches with greater discharge that are somewhat lower in a watershed than reaches used by steelhead. Ocean-type juveniles, which are typical of fall-run populations, may begin migrating toward sea within a few weeks to a few months of emergence, but some individuals may reside in streams through the summer months, before moving to estuaries during the fall or winter (Reimers, 1973; Healy, 1991; Moyle, 2002).

The suitability curves that form the basis of IP predictions for fall-run Chinook salmon reflect the dominance of gradient and discharge in determining where suitable habitats are likely to occur (Figure 1g-i). Valley constraint is less important for juvenile Fall-run Chinook, because juveniles have already gone to sea (in contrast to coho, which reside a full year in fresh water), by the time winter high-flows occur.

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[14]Analysis of environmental predictors of presence for steelhead in the South-Central California Coast ESU (D. Boughton, NOAA Fisheries, Santa Cruz Lab, *unpublished results*) suggests that mean August air temperature exceeding 24 °C might limit the distribution of steelhead, a value corroborated by similar analysis of the effects of water temperature on presence of *O. mykiss* (Eaton et al., 1995). Very little of our study area experiences these conditions.
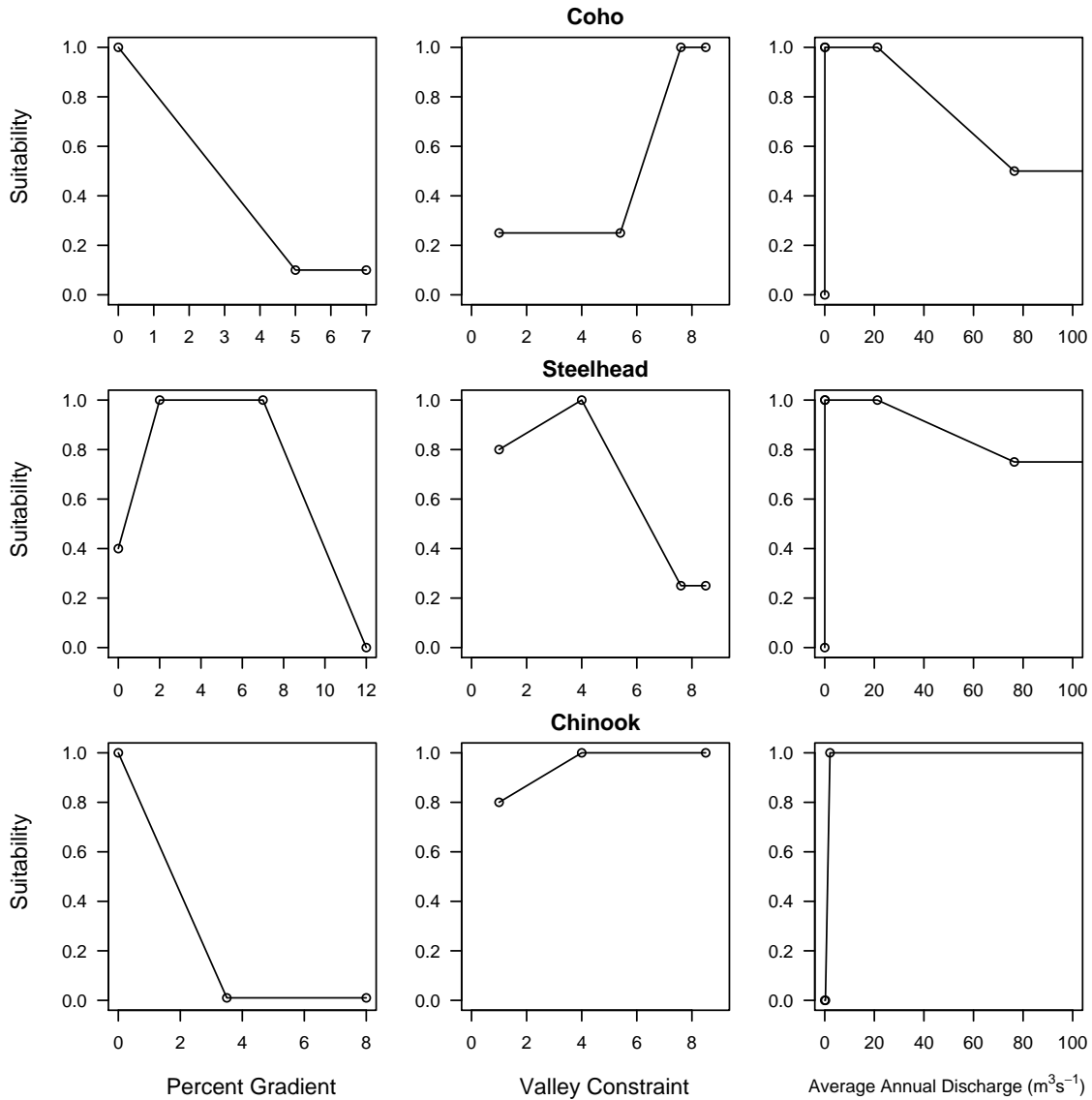
Figure 1: Suitability curves for each of the three IP components (Gradient, Valley Constraint and Discharge) for juveniles of each of the three species (coho, steelhead and chinook). Note the scale change (abscissa) across each species for the gradient attribute.

Table 1: Sources of information synthesized through expert opinion to develop suitability curves for ULEP, CLAMS, or this report.

Attribute	coho salmon	steelhead	chinook salmon
Gradient	Hicks (1989) Reeves et al. (1989) Schwartz (1991) Nickelson and Lawson (1998) Nickelson (1998) Hicks (1989) Hicks and Hall (2003) Scarnecchia and Roper (2000) Burnett (2001)	Hicks (1989) Dambacher (1991) Schwartz (1991) Roper et al. (1994) Scarnecchia and Roper (2000) Burnett (2001) Harvey et al. (2002) Engle (2002) Hicks and Hall (2003) Armantrout (2005)	Schwartz (1991) Roper et al. (1994) Scarnecchia and Roper (2000) Burnett (2001) Armantrout (2005)
Constraint	Hicks (1989) Schwartz (1991) Nickelson and Lawson (1998) Burnett (2001) Hicks and Hall (2003)	D'Angelo et al. (1995) Burnett (2001) Harvey et al. (2002) Hicks and Hall (2003)	
Discharge	Sandercock (1991) Rosenfeld et al. (2000) Burnett (2001)	Meehan and Bjornn (1991) Behnke (1992) Burnett (2001)	

3.4 Example: Ten Mile River

Plates 1, 2, and 3 illustrate examples of results from implementing the model for the Ten Mile River in Mendocino County, California. Note that while differences in the distribution of the three species are discernable, caution should be exercised when drawing this comparison. Comparison between coho or steelhead and chinook are likely not numerically equivalent, because of the issue noted with valley constraint in Section 3.3.1. Thus, for comparisons of coho salmon and steelhead an IP score of 0.7 should reflect that the reach has equal suitability for each species but possibly for different reasons. In application to chinook, IP is perhaps better used as a way to evaluate relative differences across watersheds, as opposed to direct comparisons to coho salmon or steelhead in a given watershed.

3.5 Temperature limitation for coho salmon.

Preliminary examination of IP model outputs indicated regional discrepancies between historical records and locations with high IP for juvenile coho salmon. These discrepancies were most apparent in inland areas where an additional factor, summer water temperature, might approach or exceed the tolerable limits for juvenile coho salmon (Eaton et al., 1995; Welsh, Jr. et al., 2001), and thus might preclude use of areas that otherwise appear suitable. To account for these discrepancies, we combined information on the historical distribution of coho salmon (Spence et al., in prep.) and mean August air temperature extracted from the PRISM climate data to develop temperature-based "masks." We then used these masks to exclude habitat by zeroing out the IP score for stream reaches in areas that were excessively warm for coho salmon. Specifically, we selected 335 streams for which Spence et al. (in prep.) found either (1) direct evidence of coho salmon in the form of documented first-hand observations of coho salmon presence, or (2) direct assertions by professional fishery biologists of a strong likelihood that coho salmon were present. For each of these streams, we extracted and plotted the lowest mean August air temperature (LMAT) (i.e. coolest temperature in any pixel within the polygon) for a polygon within the contributing watershed. (The polygon was defined at the mouth of the stream and included the upstream contributing area.) A pronounced decrease in the number of streams with coho salmon present was indicated as LMAT approached 21 — 22°C. Ninety five percent of watersheds known to have historically supported coho salmon had LMAT values $\leq$ 21°C and 99% had LMAT values $\leq$ 22°C (Figure 2). To support sensitivity analyses by the TRTs, we generated separate IP layers for areas with LMAT exceeding 21°C, 21.5°C, and 22°C (see, for example, Plate 4). Note

that this approach is consistent with the intrinsic potential concept; we elected not to incorporate temperature directly into the model of Burnett et al. (2003) (i.e., calculation of the geometric mean) in order to preserve comparability of predictions from the original model along the coast.

3.6 Natural Barriers

Our ability to model natural gradient barriers to fish passage depended on the resolution of DEMs. At 30 m resolution the stream model (Miller, 2003) was unable to locate anything other than massive gradient barriers in the stream. However at 10 m resolution we found that the model identified most known natural gradient barriers. The model does, however, fail to resolve barriers smaller than 10 m. For our verification, we determined how well the model picked up barriers in the Mad River (at 10 m resolution). While we did not quantify the results, it was our general impression that the model caught major barriers to anadromy. Local knowledge of a stream system and the gradient attribute of the stream layer can be used to test how well the model is working. Where the model fails to resolve known barriers, nodes can be digitized into the linework, upstream arcs can be traced, and then flagged as "behind" a barrier.

4 Interpretation and appropriate use of intrinsic potential

We used the IP modeling framework to estimate the likelihood—strictly speaking, the relative likelihood—that a stream reach will exhibit suitable habitat for juveniles of a particular species. Keeping this in mind is critical for appropriate interpretation of model results and for understanding the assumptions invoked in applying IP to estimate historical conditions. The IP models estimate neither the actual, fine-scale distribution of habitat within a basin nor the quality of habitat in a given reach under current or historical conditions. Thus, estimates of IP are likely to be relatively robust to differences in hydrology associated with seasonal and latitudinal precipitation variation, within much of the range of conditions observed in coastal watersheds of southern Oregon and northern California. In other words, stream reaches exhibiting the right combination of characteristics will likely exhibit similar propensities to provide suitable habitat. The most probable exceptions to this pattern arise in basins that exhibit substantially warmer, drier conditions, such as watersheds tributary to eastern and northern San Francisco
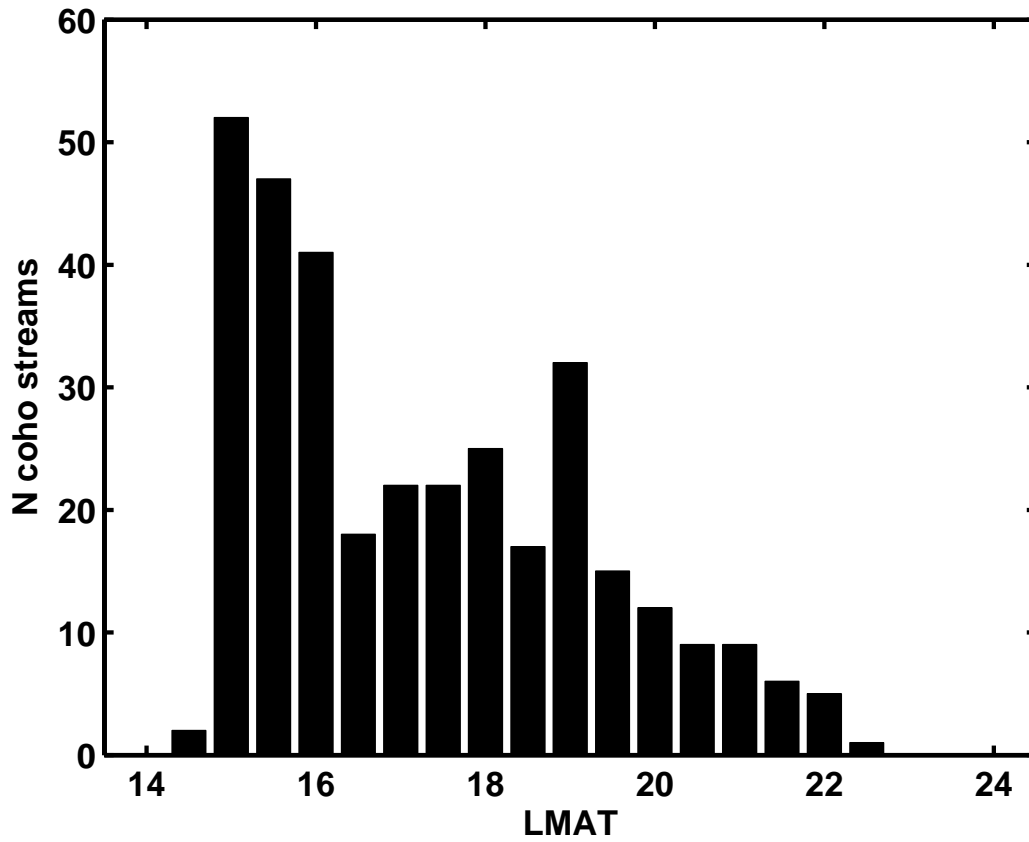
Figure 2: Lowest mean August temperature (LMAT) within catchment areas of historical coho-bearing streams in the Central California Coast Coho Salmon ESU.

Bay.

The relatively robust nature of predictions for the (relative) likelihood that suitable habitat exists almost certainly does not extend to further extrapolations from the concept of IP, such as attempts to translate predictions of IP into some measure of historical carrying capacity of a watershed (e.g. Lawson et al., in prep.; Bjorkstedt et al., in prep.; Williams et al., in prep.). Such exercises invoke assumptions regarding how IP translates into a measure of habitat capacity and, in turn, into a measure of fish abundance. These assumptions are likely to be sensitive to differences in climate that affect how seasonal winter precipitation affects summer stream discharge. This is particularly important if a latitudinal gradient in the relative importance of winter versus summer habitat limits population size or productivity in coho salmon and steelhead. An analogous issue arises for Fall-run Chinook salmon for which the timing and intensity of early winter storms can strongly affect the ability of these fish to enter freshwater. Thus, any use of IP that goes beyond interpreting it relative to habitat suitability requires careful consideration of the assumptions and potential biases that arise from any violation of these assumptions.

5   Description of the GIS database

5.1   Distribution

The IP and stream data are available for distribution as GIS coverages in .e00 form (ESRI proprietary export and interchange file type). Please contact Dr. Peter Adams, Fisheries Branch Chief, Southwest Fisheries Science Center, Santa Cruz Laboratory, at 831-420-3923, or Pete.Adams@noaa.gov for information on how to acquire the data. The data are available for all anadromous populations in our purview. This ranges from the Rogue River basin in Southern Oregon to the Tijuana River in Southern CA, and includes the steelhead ESU in the Central Valley, however, IP implementation in the Central Valley and Southern California recovery domains is different from that noted here. Consult Lindley et al. (in prep.) and Boughton (in prep.) for specifics of those implementations. We have created a master metadata file that describes, in detail, each of the attributes generated at the different processing steps. Where a given watershed exists in multiple ESUs, the IP coverages contains IP information for the different species. Streams in the NCCC also include summaries of the temperature masked IP (See §3.5). Lastly, there are no current plans to update the IP streams; they are distributed as is.

5.2 Usage within a GIS

The IP data exist for all watersheds containing anadromous populations of salmonids in our study area (Southern OR to the CA/Mexico border). For large watersheds with multiple sub-populations, we have delineated the areal extent of the sub-populations and calculated IP at that level. For example in the Klamath River, we have IP streams for the Scott, the Shasta, and the Salmon, etc., but not for the entire Klamath basin. (Since the files are at 1:24k, the Microsoft Windows file size limit constrains total size.) Several of the smaller coastal basins were lumped and calculated as one watershed. The streams data are at approximately a 1:24k scale; however, the data do not contain stream names or other identifying attributes (e.g. LLID), nor does a route system exist for the streams. To locate IP on particular reaches on specific named streams, one would have to navigate using a named stream system, e.g. CA 1:100k routed hydrography (Christy, 2003) (see Data Downloads section of http://www.calfish.org; available for download at ftp://ftp.streamnet.org/pub/calfish/cdfg_100k_2003_6.zip). With the following attributes: co_ip_curve (coho), chk_ip_curve (chinook), and st_ip_curve12 (steelhead) and a graduated color ramp within the GIS, users can recreate the figures shown herein. Consult the metadata for specifics on the additional attributes within the data layer.

6 Acknowledgements

References

Agajanian, J., G. L. Rockwell, S. W. Anderson, and G. L. Pope. 2002. Water resources data, California water year 2001, Volume 1. Technical Report USGS-WDR-CA-01-1, U. S. Department of the Interior, U. S. Geological Survey.

Armantrout, N. B. 1995. Defining aquatic habitat through remote sensing. Paper presented at the 1995 Asian Fisheries Society Meeting, Beijing, China.

Behnke, R. J. 1992. Native trout of western North America. American Fisheries Society Monograph 6. American Fisheries Society, Bethesda, Maryland.

Bell, E., W. G. Duffy, and T. D. Roelofs. 2001. Fidelity and survival of juvenile coho salmon in response to a flood. Transactions of the American Fisheries Society 130:450–458.

Benda, L. 1994. Stochastic geomorphology in a humid mountain landscape. Ph.D. thesis, University of Washington, Seattle, Washington.

Bisson, P. A., K. Sullivan, and J. L. Nielsen. 1988. Channel hydraulics, habitat use, and body form of juvenile coho salmon, steelhead, and cutthroat trout in streams. Transactions of the American Fisheries Society 117:262–273.

Bjorkstedt, E. P., B. C. Spence, J. C. Garza, D. G. Hankin, D. Fuller, W. Jones, J. J. Smith, and R. Macedo. In prep. An analysis of historical population structure for evolutionarily significant units of coho salmon, Chinook salmon, and steelhead in the North-Central California Coast Recovery Domain. NOAA Technical Memorandum NOAA-TM-NMFS-SWFSC-XXX.

Boughton, D. In prep. Potential unimpaired steelhead habitat in the southern domain, CA. NOAA Technical Memorandum NOAA-TM-NMFS-SWFSC-XXX.

Bugert, R. M., and T. C. Bjornn. 1991. Habitat use by steelhead and coho salmon and their responses to predators and cover in the laboratory. Transactions of the American Fisheries Society 120:486–493.

Burnett, K. M. 2001. Relationships among juvenile anadromous salmonids, their freshwater habitat, and landscape characteristics over multiple years and spatial scales in the Elk River, Oregon. Ph.D. thesis, Oregon State University, Corvallis, Oregon.

Burnett, K. M., G. Reeves, D. Miller, S. Clarke, K. Christiansen, and K. Vance-Borland, 2003. A first step toward broad-scale identification of freshwater protected areas for Pacific salmon and trout in Oregon, USA. Pages 144–154 *in* J. P. Beumer, A. Grant, and D. C. Smith, editors. Aquatic Protected Areas: what works best and how do we know? Proceedings of the 3rd World Congress on Aquatic Protected Areas. Australian Society for Fish Biology, Cairns, Australia.

Christy, T., 2003. 1:100K hydrography, version 2003.4. California Department of Fish and Game (available at http://www.calfish.org).

Daly, C., R. P. Neilson, and D. L. Phillips. 1994. A statistical-topographic model for mapping climatological precipitation over mountainous terrain. Journal of Applied Meteorology 33:140–158.

Dambacher, J. M. 1991. Distribution, abundance, and emigration of juvenile steelhead (*Oncorhynchus mykiss*), and analysis of stream habitat in the Steamboat Creek basin, Oregon. Master's thesis, Oregon State University, Corvallis, Oregon.

D'Angelo, D. J., L. M. Howar, J. L. Meyer, S. V. Gregory, and L. R. Ashkenas. 1995. Ecological uses for genetic algorithms: predicting fish distributions in complex physical habitats. Canadian Journal of Fisheries and Aquatic Sciences 52:1893–1908.

Eaton, J. G., J. H. McCormic, H. G. Stefan, and M. Hondzo. 1995. Extreme value analysis of a fish/temperature field database. Ecological Engineering 4:289–305.

Engle, R. O. 2002. Distribution and summer survival of juvenile steelhead trout (*Oncorhynchus mykiss*) in two streams within King Range National Conservation Area, California. Master's thesis, Humboldt State University, Arcata, California.

Fire and Resource Assessment Program (FRAP). 1999. California watersheds (CALWATER 2.2). California Department of Forestry and Fire Protection, FRAP. Available: http://gis.ca.gov/meta.epl?oid=5298.

Frissell, C. A., W. J. Liss, C. E. Warren, and M. D. Hurley. 1986. A hierarchial framework for stream habitat classification: viewing streams in a watershed context. Environmental Management 10:199–214.

Harvey, B. C., J. L. White, and R. J. Nakamoto. 2002. Habitat relationships and larval drift of native and nonindigenous fishes in neighboring tributaries of a coastal California river. Transactions of the American Fisheries Society 131:159–170.

Healy, M. C. 1991. The life history of chinook salmon. Pages 311–393 *in* C. Groot and L. Margolis, editors. Pacific Salmon Life Histories. University of British Columbia Press, Vancouver, British Columbia.

Hicks, B. J. 1989. The influence of geology and timber harvest on channel morphology and salmonid populations in Oregon Coat Range streams. Ph.D. thesis, Oregon State University, Corvallis, Oregon.

Hicks, B. J., and J. D. Hall. 2003. Rock type and channel gradient structure salmonid populations in the Oregon Coast Range. Transactions of the American Fisheries Society 132:468–482.

Lawson, P. W., E. P. Bjorkstedt, C. Huntington, T. Nickelson, G. L. Reeves, H. A. Stout, and T. C. Wainwright. In prep. Identification of historical populations of coho salmon (*Oncorhynchus kisutch*) in the Oregon Coast Evolutionarily Significant Unit. NOAA Technical Memorandum NOAA-TM-NMFS-NWFSC-XXX.

Lindley, S., R. Schick, and A. Agrawal. In prep. Historical population structure of Central Valley steelhead. NOAA Technical Memorandum NOAA-TM-NMFS-SWFSC-XXX.

Lorensen, T., C. Andrus, and J. Runyon, 1994. The Oregon Forest Practices Act Water Protection Rules: scientific and policy considerations. Oregon Department of Forestry, Forest Practices Policy Unit, Salem, Oregon.

McElhany, P., M. H. Ruckelshaus, M. J. Ford, T. C. Wainwright, and E. P. Bjorkstedt. 2000. Viable salmonid populations and the recovery of evolutionarily significant units. NOAA Technical Memorandum, NMFS-NWFSC-42.

Meehan, W. R., and T. C. Bjornn. 1991. Salmonid distributions and life histories. American Fisheries Society Special Publication 19:47–82.

Meffe, G. K., and R. C. Vrijenhoek. 1988. Conservation Genetics in the Management of Desert Fishes. Conservation Biology 2:157–169.

Miller, D. 2003. Programs for DEM analysis. Earth Systems Institute, Seattle, Washington

Montgomery, D. R., and J. M. Buffington. 1998. Channel processes, classification, and response. Pages 13–42 *in* J. R. Naiman and R. E. Bilby, editors. River ecology and management lessons from the Pacific Coastal Region. Springer, New York.

Moyle, P. B. 2002. Inland Fishes of California (Revised and Expanded). University of California Press, Berkeley, California.

National Resources Conservation Service (NRCS). 2002. 8, 10, and 12 digit HUs for Oregon, Washington, and northern California. U.S. Department of Agriculture, NRCS, Titan Geospatial (available at http://www.gis.state.or.us).

Nickelson, T. E. 1998. A habitat-based assessment of coho salmon production potential and spawner escapement needs for Oregon coastal streams. Oregon Information Reports 98-4, Oregon Department of Fish and Wildlife, Portland, Oregon.

Nickelson, T. E., and P. W. Lawson. 1998. Population viability of coho salmon, *Oncorhynchus kisutch*, in Oregon coastal basins: application of a habitat-based life cycle model. Canadian Journal of Fisheries and Aquatic Sciences 55:2383–2392.

Reeves, G. H., F. H. Everest, and T. E. Nickelson. 1989. Identification of physical habitats limiting the production of coho salmon in western Oregon and Washington. General Technical Report PNW-GTR-245, U.S. Forest Service, Pacific Northwest Research Station. Portland, Oregon.

Reimers, P. E. 1973. The length of residence of juvenile fall chinook salmon in Sixes River, Oregon. Research Reports of the Fish Commission of Oregon 4:1–43.

Roper, B. B., D. L. Scarnecchia, and T. J. LaMarr. 1994. Summer distribution of and habitat use by chinook salmon and steelhead within a major basin of the South Umpqua River, Oregon. Transactions of the American Fisheries Society 123:298–308.

Rosenfeld, J., M. Porter, and E. Parkinson. 2000. Habitat factors affecting the abundance and distribution of juvenile cutthroat trout (*Oncorhynchus clarki*) and coho salmon (*Oncorhynchus kisutch*). Canadian Journal of Fisheries and Aquatic Sciences 57:766–774.

Sandercock, F. K. 1991. Life history of coho salmon (*Oncorhynchus kisutch*). Pages 395–446 *in* C. Groot and L. Margolis, editors. Pacific salmon life histories. University of British Columbia Press, Vancouver, British Columbia.

Scarnecchia, D. L., and B. B. Roper. 2000. Large-scale, differential summer habitat use of three anadromous salmonids in a large river basin in Oregon, USA. Fisheries Management and Ecology 7:197–209.

Schwartz, J. S. 1991. Influence of geomorphology and land use on distribution and abundance of salmonids in a coastal Oregon Basin. Master's thesis, Oregon State University, Corvallis, Oregon.

Smith, J. J., and H. W. Li, 1983. Energetic factors influencing foraging tactics of juvenile steelhead trout, *Salmo gairdneri*. Pages 173 – 180 *in* D. L. G. Noakes, editor. Predators and prey in fishes: proceedings of the 3rd biennial conference on the Ethology and Behavioral Ecology of Fishes, held at Normal, Illinois, U.S.A., May 19-22, 1981. W. Junk, The Hague.

Solley, W. B., R. R. Pierce, and H. A. Perlman. 1998. Estimated use of water in the United States in 1995. Technical report, U. S. Department of the Interior, U. S. Geological Society.

Spence, B. C., S. Harris, and W. Jones. In prep. Historical occurrence of coho salmon in streams of the Central California Coast Coho Salmon Evolutionarily Significant Unit. NOAA Technical Memorandum NOAA-TM-NMFS-SWFSC-XXX.

Tarboton, D. G. 1997. A new method for the determination of flow directions and upslope areas in grid digital elevation models. Water Resources Research 33:309–319.

Tschaplinski, P. J., and G. F. Hartman. 1983. Winter distribution of juvenile coho salmon (*Oncorhynchus kisutch*) before and after logging in Carnation Creek, British Columbia, and some implications for overwinter survival. Canadian Journal of Fisheries and Aquatic Sciences 40:452–461.

USGS. 2003. National hydrography dataset. U.S. Department of the Interior, U.S. Geological Survey. (available at http://nhd.usgs.gov).

Vogelman, J. E., S. M. Howard, L. Yang, C. R. Larson, B. K. Wylie, and N. V. Driel. 2000. Completion of the 1990s National Land Cover Data Set for the coterminous United States from Landsat Thematic Mapper data and ancillary data sources. Photogramm. Eng. Remote Sensing 67:650–652.

Welsh, Jr., H. H., G. R. Hodgson, and B. C. Harvey. 2001. Distribution of juvenile coho salmon in relation to water temperatures in tributaries of the Mattole River, California. North American Journal of Fisheries Management 21:464–470.

Williams, T. H., E. P. Bjorkstedt, W. Duffy, D. Hillemeier, G. Kautsky, T. Lisle, M. McCain, and M. Rode. In prep. Population structure of threatened coho salmon in the Southern Oregon/Northern California Coast Evolutionarily Significant Unit. NOAA Technical Memorandum NOAA-TM-NMFS-SWFSC-XXX.

Young, K. A. 2004. Asymmetric competition, habitat selection, and niche overlap in juvenile salmonids. Ecology 85:134–149.

Coho IP
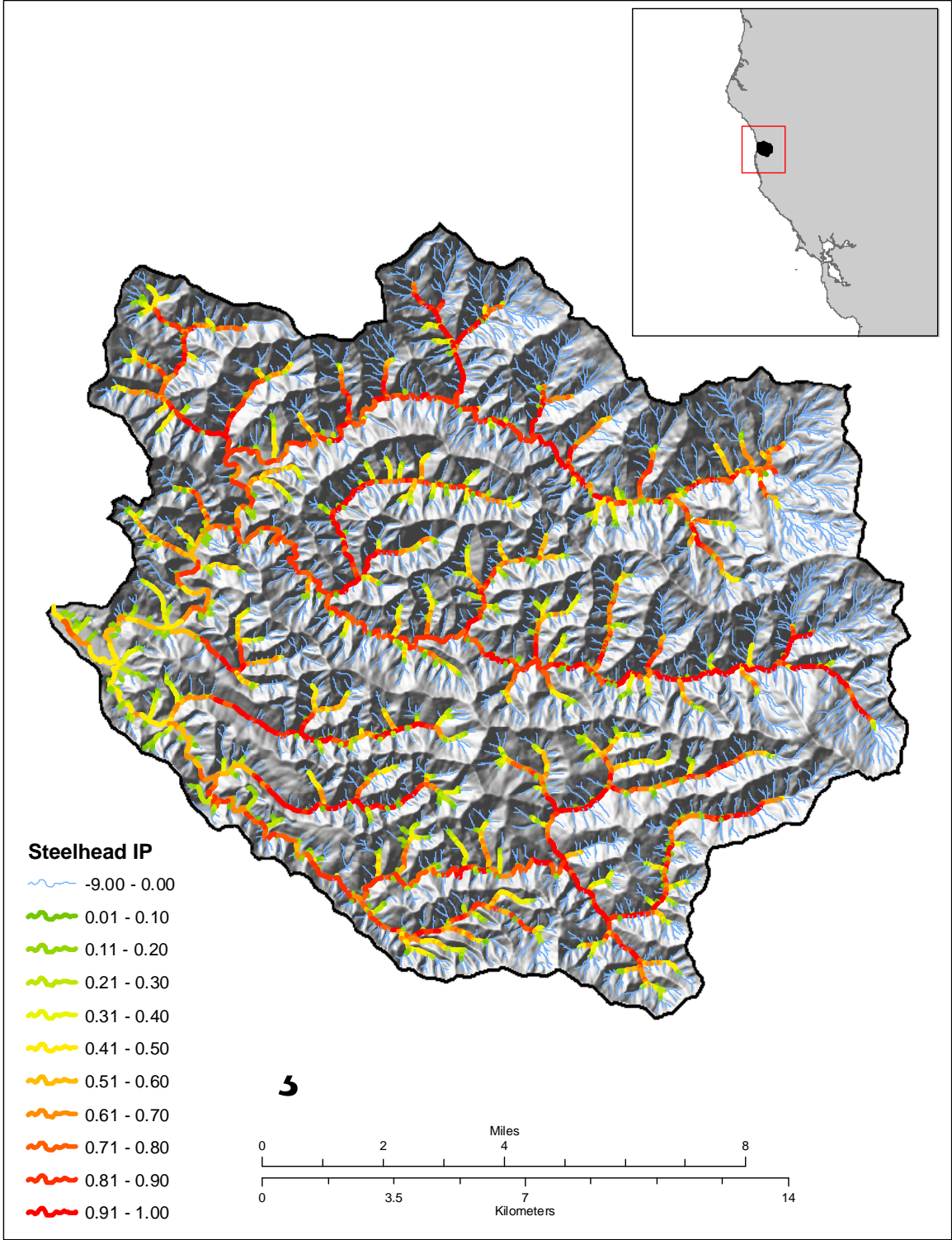
- ~~~~ -9.00 - 0.00
- ~~~~ 0.01 - 0.10
- ~~~~ 0.11 - 0.20
- ~~~~ 0.21 - 0.30
- ~~~~ 0.31 - 0.40
- ~~~~ 0.41 - 0.50
- ~~~~ 0.51 - 0.60
- ~~~~ 0.61 - 0.70
- ~~~~ 0.71 - 0.80
- ~~~~ 0.81 - 0.90
- ~~~~ 0.91 - 1.00

Miles
0   2   4   8
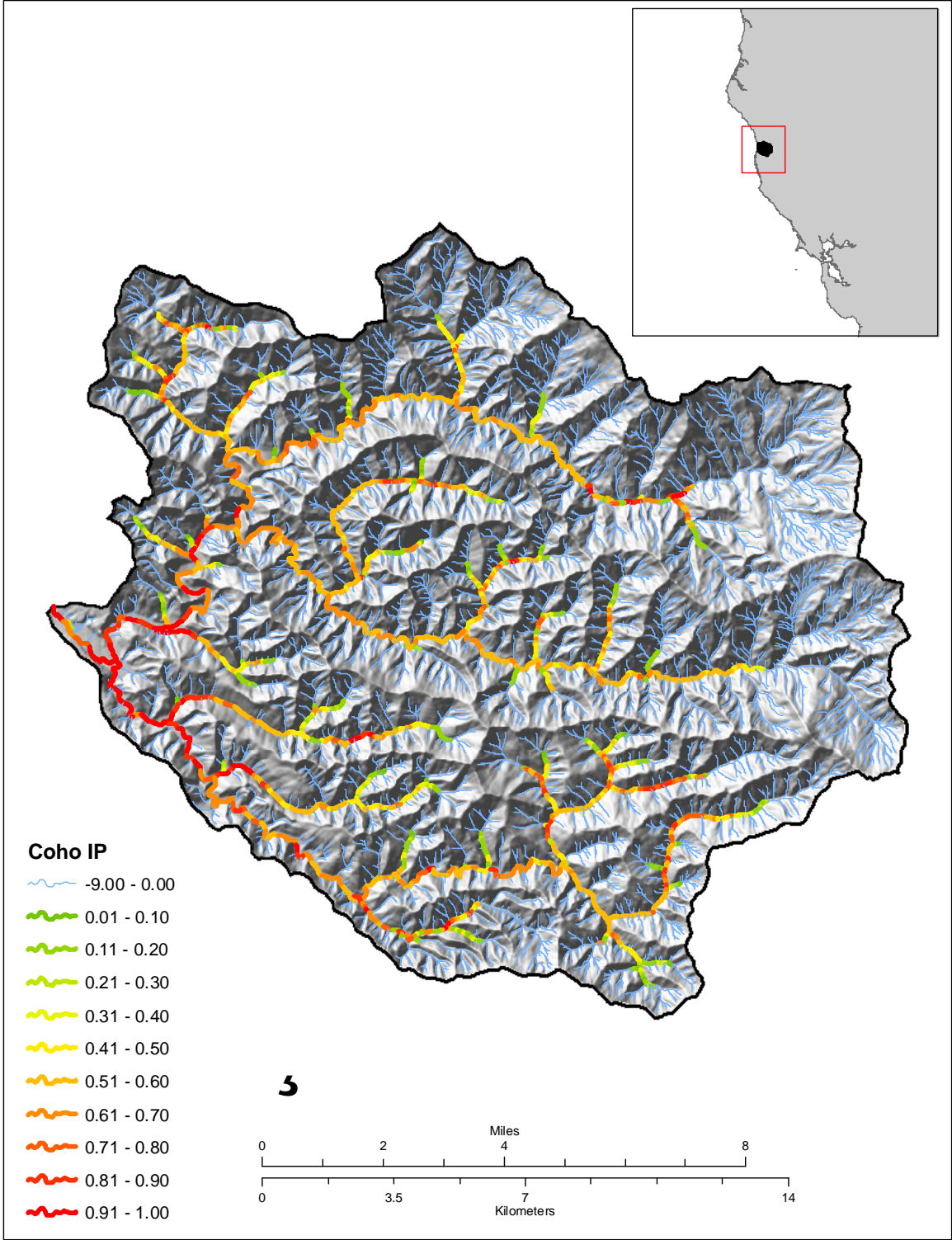
0   3.5   7   14
Kilometers

Plate 1: Intrinsic potential for coho salmon rearing habitat for the Ten Mile River.

Plate 2: Intrinsic potential for winter steelhead rearing habitat for the Ten Mile River.

Chinook IP

- ~~~ -9.00 - 0.00
- ~~~ 0.01 - 0.10
- ~~~ 0.11 - 0.20
- ~~~ 0.21 - 0.30
- ~~~ 0.31 - 0.40
- ~~~ 0.41 - 0.50
- ~~~ 0.51 - 0.60
- ~~~ 0.61 - 0.70
- ~~~ 0.71 - 0.80
- ~~~ 0.81 - 0.90
- ~~~ 0.91 - 1.00

Miles
0   2   4   8
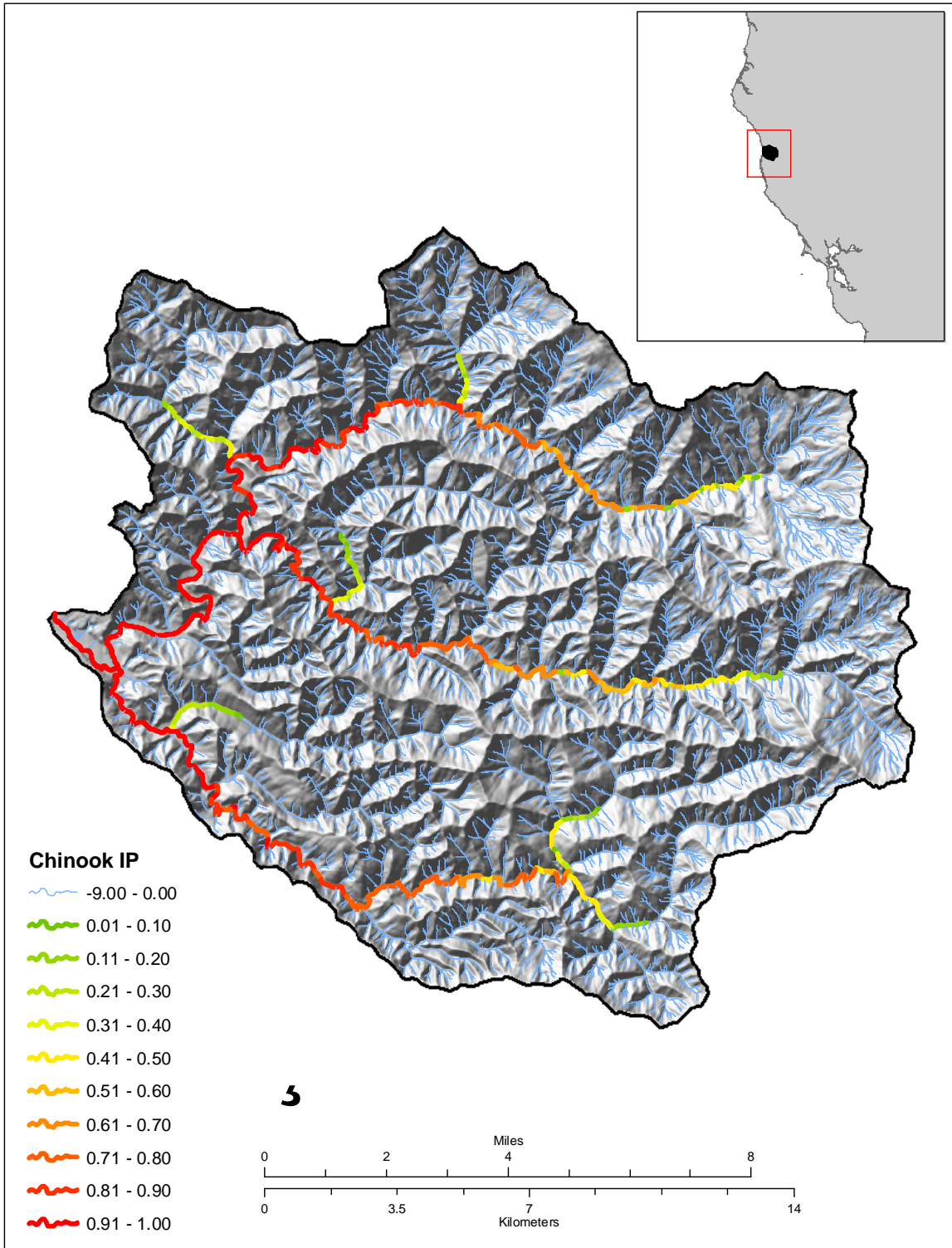
0   3.5   7   14
Kilometers

Plate 3: Intrinsic potential for fall-run Chinook salmon spawning and rearing habitat for the Ten Mile River.
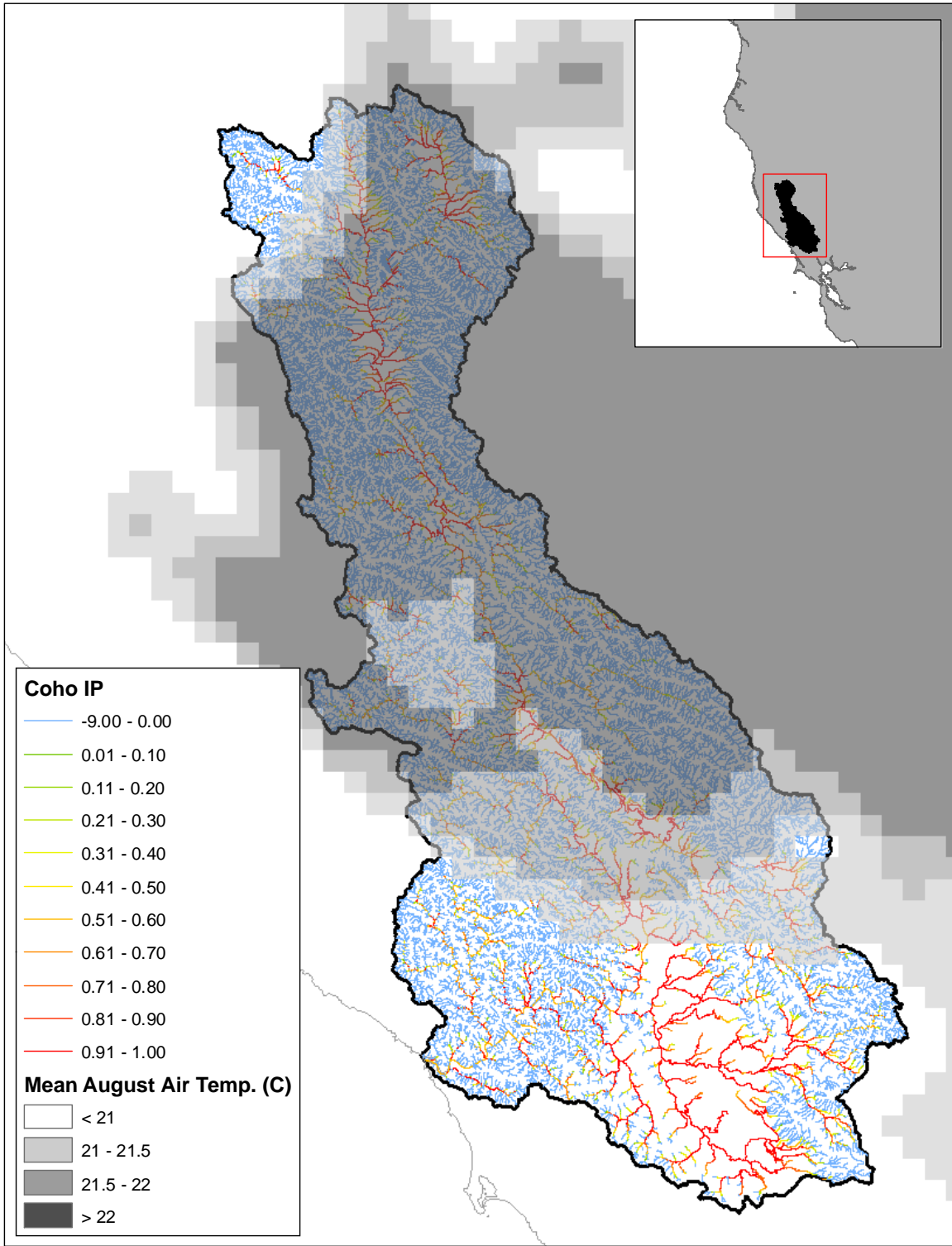
Plate 4: Intrinsic potential for coho salmon rearing habitat in the Russian River with areas from which coho salmon are likely to be excluded by high summer temperatures.

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